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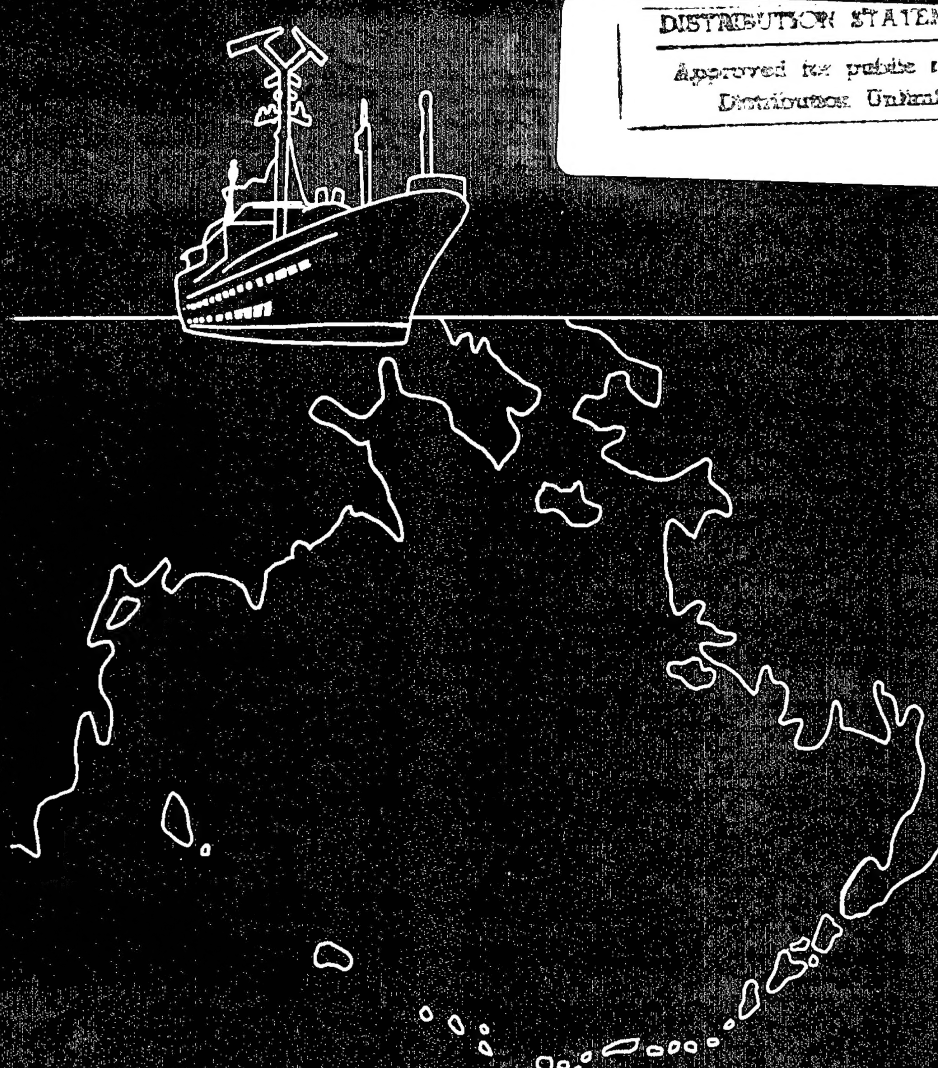
RESULTS OF THE SECOND JOINT U.S.-U.S.S.R. BERING SEA EXPEDITION SUMMER 1984



Fish and Wildlife Service
U.S. Department of the Interior

U.S.S.R. State Committee on Hydrometerology and Natural Enrvionmental Control

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Results of the Second Joint U.S.-U.S.S.R. Bering Sea Expedition, Summer 1984

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U.S.S.R. State Committee on Hydrometeorology and Natural Environmental Control

U.S. Department of the Interior
Fish and Wildlife Service

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Editor's Note

While every effort was made to produce a consistent document in both English and Russian, differences in language, style, and manuscript preparation were unavoidable in the text of the U.S. and U.S.S.R. papers. These differences are most obvious in the bibliographies accompanying the U.S.S.R. papers; however, the graphs and tables were assiduously reproduced in both texts. Readers should note that the results of the 1977 Bering Sea expedition are available under the title *Joint U.S.A.-U.S.S.R. Ecosystem Investigation of the Bering Sea July-August, 1977.* The Library of Congress number of the publication is 82-084513.

Foreword

Changes in the biosphere in the last few decades has resulted in the realization of the fragility and interdependence of human civilizations and the need for international cooperation to protect our environment. The ever-growing anthropogenic loading of different natural ecosystems and expansion of anthropogenic impact areas call for comprehensive integrated environmental analyses and establishment of global ecological monitoring systems. Such efforts will make it possible to turn to a scientifically based and rational utilization of nature.

The bulk of all chemical compounds produced by humans enter the world's oceans, which now represent a gigantic reservoir. Cycling within this reservoir causes pollutants to be partially removed naturally by self-purification processes. However, under the influence of this ever acting factor, life-favoring abiotic and biotic regimes which have been established in the ocean over whole geological epochs are being disturbed.

In order to study ocean pollution and its ecological consequences, researchers must conduct numerous physical, chemical, and biological investigations. These investigations have required new interdisciplinary approaches. These approaches are making it possible to develop new theoretical concepts of marine ecosystem stability, to investigate the dynamics of pollutant input and elimination from marine ecosystems, and to study the mechanisms of responses of living matter at different levels of its organization--from cell to ecosystem. To isolate the anthropogenic effects from the background of natural variability and to develop the principles of sound ecological ocean monitoring, it is necessary to conduct lengthy observations of physical (hydrological regimes), geochemical (turnover of biogenic substances and pollutants), and hydrobiological (ecological metabolism, changes in the structural and functional characteristics of planktonic and benthic communities) processes. Investigations of properties of marine organisms and their communities (processes of microbial destruction of pollutants and the latter's influence on the functions of hydrobionts) are also needed. Results obtained will make it possible to elucidate the theoretical concepts of the quality of the marine environment and to assess the tolerance of aquatic ecosystems to pollutants. In addition, such data could be used to develop long-term forecasting of the state of the world's oceans.

Investigations of this nature are of particular interest since they make it possible to trace the dynamics of environmental changes under the impact of anthropogenic factors over vast areas of the open ocean.

From our viewpoint, the Bering Sea is exceptionally suited to performing a comprehensive ecological analysis of the state of pristine regions. The degree and character of the anthropogenic impacts on its ecosystem reflect to a large measure similar processes occurring in the world's oceans.

Since the Bering Sea washes the borders of two counties, the U.S.S.R. and the U.S.A., which are equally concerned with the environmental health of this unique region, it seems most fruitful to study this region by combining the efforts and expertise of scientists from both countries.

In accordance with the Memorandum of the VIth session of the Joint Soviet-American

Commission on Cooperation in the Field of the Protection of the Environment in the framework of the project on Biosphere Reserves, two Soviet-American integrated ecological expeditions were conducted to study the Bering Sea ecosystem. These joint expeditions made it possible to expand our knowledge of this insufficiently explored body of water.

Research emphasis included the study of the oceanographic regime in greater detail, accumulation of data on the seasonal and vertical variability of nutrient concentrations, acquisition of data on ecological metabolism, structural and functional characteristics of planktonic and benthic communities, and determination of the role of microorganisms in the biogeochemical cycles of elements and in the destruction of organic pollutants.

The first expedition in the Bering Sea in 1977, on board the U.S.S.R. RV *Volna* initiated long-term integrated investigations of the Bering Sea. The basic scientific results of the expedition are described in the monograph *Joint U.S.A.-U.S.S.R. Ecosystem Investigation of the Bering Sea July-August, 1977,* published in both the Soviet Union and the United States.

These investigations were continued during the integrated ecological expedition carried out by Soviet specialists in 1981 on board the research vessel *Akademik Shirshov*. During this expedition, new scientific data were obtained characterizing the state of the Bering Sea ecosystem, the composition and physiological activity of bacterial populations, quantitative and qualitative composition of microzooplankton, and biogeochemical cycles of polyaromatic hydrocarbons including metabolism of benzo(a)pyrene, which was investigated for the first time. Scientific results of the expedition were published in the monograph *Comprehensive Analysis of the Bering Sea Ecosystem.*

The second integrated ecological Soviet-American expedition on board the RV *Akademik Korolev* was conducted in 1984. During that expedition, a broad spectrum of problems described in the present monograph was investigated. The problems included a study of oceanographic aspects, hydrochemical regimes, variability of the spatial structure of planktonic biocoenoses, microbial distribution of organic pollutants, impact of toxicants on the in situ state of planktonic communities, assessment of the elements of the ecosystem balance, the balance between the new formation and degradation of organic matter in the ecosystem, determination of the elements of the biogeochemical cycles of organic pollutants, and scientific approaches to the determination of the environmental capacity of the Bering Sea.

Based on these investigations it was concluded that the Bering Sea ecosystem is now at equilibrium. To preserve this situation under conditions of expanding anthropogenic loadings by both countries, however, a scientific approach to the utilization of the natural resources of this unique region is necessary. Development of this approach is promoted by scientific information obtained in the course of our joint ecological expeditions.

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Contents

Acknowledgments

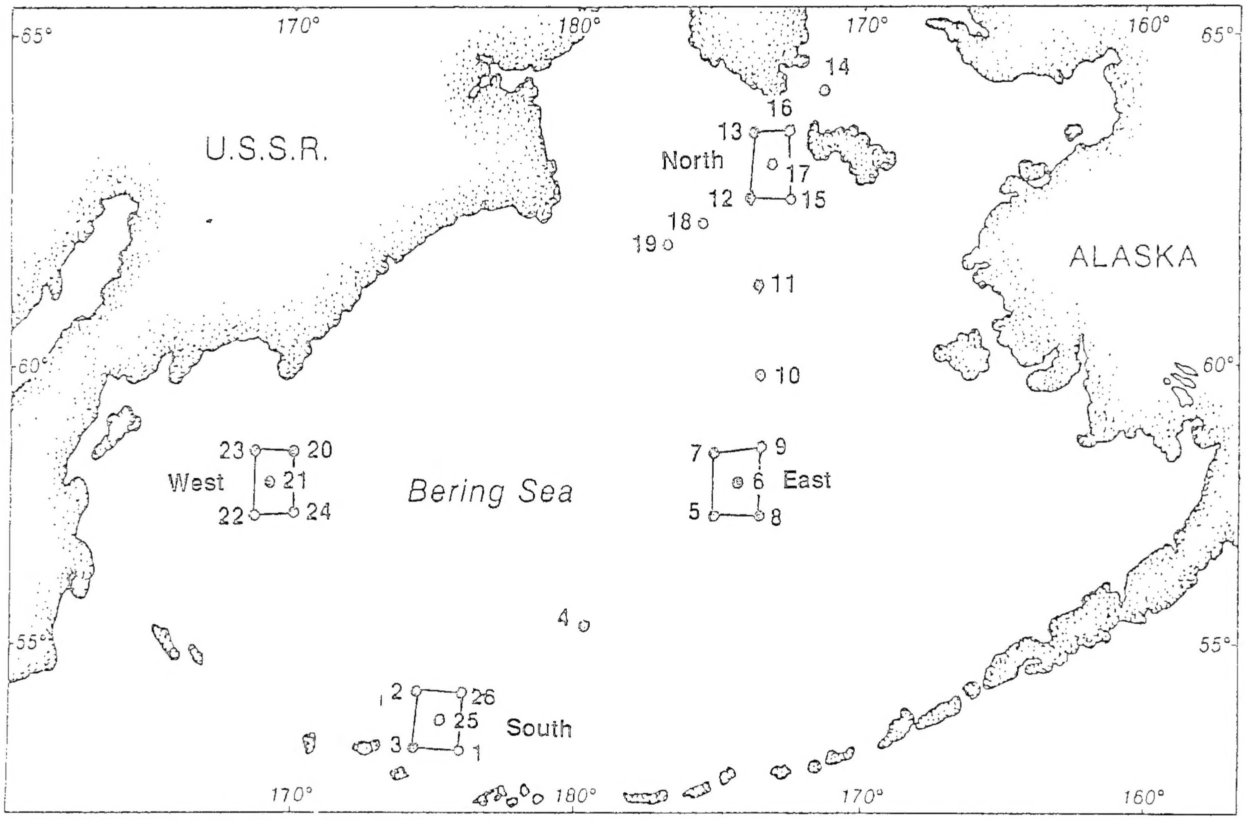
Over the last 12 years of my involvement with Bering Sea Studies project, I have met many selfless people who have volunteered their time and effort to see this project to completion. A cadre of Americans and Soviets have contributed so much because the personal friendships that developed from our working relationships quickly transcended science and politics. At times this good will and fellowship literally sustained the project during some very difficult periods. That the project has persevered and flourished is a testimony to a Quixotic spirit that allows so many different people to care so very much about this project.

My very special thanks go to Hal O'Connor, Bob Putz, and Steve Kohl for their support over the years. Eckart Schroeder deserves special recognition for his efforts in insuring the high quality of our ship-board power supply. I am grateful to Lynn Luckhurst, Gerry Reid, and Stephanie Miller for their efforts. I would also like to acknowledge the support of Jimmy Johnston, Jerry Grau, and Bob Stewart for allowing me to continue working on this project while at my present position. Gaye Farris and her production team of Sue Lauritzen, Camilla Wiik, Daisy Singleton, Joyce Rodberg, and Charmaine Cooper deserve special recognition for the excellent effort and for their patience during the rush to publication. My deepest thanks go to Beth Vairin who, in spite of my best efforts to the contrary, made this a better document.

My gratitude to my Soviet and American colleagues can not be adequately expressed. I learned much from them and will always cherish the memories. I especially thank Alla Tsyban and Terry Whitledge for all that they have done.

Many who participated on the cruise will remember John J.A. McLaughlin and his contribution to this project. Even though he has left us, his spirit and good will always exist among those who had the pleasure of knowing him. To his memory, I would like to dedicate this work.

P.F.R.



Frontispiece. Polygons and sampling stations on the Second Joint U.S.-U.S.S.R. Bering Sea Expedition.

Locations of the stations on the expedition.

Station	Latitude	Longitude	Station	Latitude	Longitude
1	53°16'08"N	177°07'04"E	14	64°21'00"N	171°23'00"W
2	54°16"07"N	175°19'01"E	15	62°58'09"N	172°30'02"W
3	53°15'07"N	175°20'00"E	16	63°59'05"N	172°30'00"W
4	56°27'00"N	178°55'08"W	17	63°29'00"N	173°01'09"W
5	57°27"06"N	176°03'07"W	18	62°44'04"N	174°39'01"W
6	58°03'01"N	175°14'02"W	19	62°30'00"N	175°48'04"W
7	58°30'04"N	176°07'04"W	20	58°30'04"N	170°28'08"E
8	57°34'04"N	174°08'06"W	21	58°00'08"N	170°01'06"E
9	58°32'04"N	174°07'09"W	22	57°30'00"N	169°30'00"E
10	60°01'00"N	173°55'09"W	23	58°30'08"N	169°25'07"E
11	61°30'08"N	173°40'00"W	24	57°26'09"N	170°29'04"E
12	63°05'00"N	173°27'09"W	25	53°44'07"N	176°09'08"E
13	63°59'08"N	173°30'00"W	26	57°15'06"N	177°00'02"E

Introduction to the Problem

CURRENT STATE OF POLLUTANTS IN THE WORLD OCEAN

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Introduction

The impact of human development on the World Ocean is one of the primary concerns among the many contemporary problems resulting from human interaction with the environment. The ocean plays a critical role in the functioning of the Earth's ecosystem and thus in the maintenance of this planet for human habitability. Through the ocean's compensatory biogeochemical cycles, much of the earth's oxygen supply is generated; large amounts of pollutant carbon dioxide are removed from the atmosphere; global climate and weather patterns are influenced; and large amounts of food, energy, and mineral resources are provided. The World Ocean, "the cradle of life on earth," has been exploited with increasing frequency during this century for its rich resources.

Since 1950, world landings of commercially important fish species have more than tripled. This increase in exploitation occurred because new technologies allowed for the prompt location of fisheries, the efficient landing of resources, and the rapid processing and transportation of fish products (Laevstu and Hayes 1981). As our knowledge of oceanography has grown, our ability to use this knowledge has produced annual fish harvests of 71 million metric tons (Voytov 1986), with new commercial markets being developed for krill, shellfish, and other resources.

More than 50 billion dollars (USA), 99% of the annual world catch, comes from coastal wetlands and estuaries and the waters extending 320 km offshore (O'Bannon 1988). Thus, these valuable ocean margins provide the required spawning, nursery, and feeding grounds for many heavily exploited fishery resources. With serious malnutrition affecting 15% of the world's population, the ocean's margins are indispensable contributors to the nutritional needs of the expanding global population (Klod 1978; Anon. 1983).

Unfortunately, the rapid growth of industrialization and urbanization has placed a great deal

of stress on these same waters. The number of people living in coastal regions is expected to double by the beginning of the 21st century. Perhaps as much as 90% of the domestic sewage and a majority of the industrial waste generated by this population will be dumped into the ocean without primary treatment (Novikov 1983).

The environmental stress is already apparent as over-fishing of resources (Hempel 1987), loss of valuable wetland habitat to urbanization and agricultural use (Council on Environmental Quality 1978), and elevated levels of pollutants in coastal waters (Abdullah et al. 1972; Levy 1980). Ironically, as man has become more dependent on marine biological resources, associated anthropogenic effects imperil the processes that sustain marine ecosystems.

Certainly, the ocean is capable of absorbing some level of industrial and domestic effluents without deleterious effect (Goldberg 1981). However, the ecological effects of these substances exceed our present understanding. Knowledge of the assimilative capacity of marine ecosystems to absorb such inputs is needed, but at present, the complex chemical and biological transformations defining these capacities have yet to be totally understood and quantified. The following is a brief discussion of some human activities that impact the World Ocean.

Mineral Resource Development

The ocean possesses a seemingly inexhaustible supply of mineral resources such as ilmenite, rutile, magnetite, gold, platinum, and tantalo-niobate. Shallow offshore deposits of building materials (sand, gravel, shells, and limestone) are accessible to coastal markets and available through current technology. In general, the low concentrations of most dissolved substances (except for magnesium, bromine, and sodium) make practical extraction of these minerals prohibitive because suitable technology is lacking and energy requirements are great (Anon. 1985b).

However, a potential area of exploitation that is embroiled in controversy concerns the issue of seabed mining for manganese nodules (ferric-manganese concretions) (Sorokin 1972). As one of many disputes concerning the United Nations' Conference on the Law of the Sea (UNCLOS), adequate treatment of seabed mining (NOAA 1977) is beyond the scope of this paper. Many of the political and economic ramifications of UNCLOS remain a matter of great debate (Burke 1983). However, while a case can be made that seabed mining is less environmentally harmful than terrestrial mining (e.g., acid mine drainage, erosion, and groundwater contamination), the suction-dredge activity needed to remove nodules may have a severe impact on fragile and unique benthic habitats and communities. The consequences of such actions on the poorly understood benthic food webs (Mills 1975) may disrupt renewable marine resources.

Oil and Gas Production and Exploration

More than 90% of all nonrenewable resources extracted from the ocean are petroleum and natural gas. With about 78 countries globally developing these resources (Klod 1978; Brabin 1986), about 4.0 million metric tons of petroleum hydrocarbons enter the ocean annually from all sources. This amount represents about 0.23% of the total yearly world extraction of petroleum (Gunkel and Gassman 1980; Levi 1984).

The growth of industry and trade has relied on the ocean, not only as a source of energy, but also as an important means of transportation. Commercial shipping accounts for a large proportion of trade in the world economy. For example, in 1980 alone, 3,773 billion metric tons of marine cargo were shipped (Anon. 1985a). Unfortunately, ocean currents are an excellent vehicle for spreading contamination from accidental oil spills, so that marine transportation and industrial activity are a major source of ocean oil pollution in all parts of the world (about 2.9 million metric tons of

petroleum per year) (Atlas et al. 1981; Levi 1984).

The total volume of oil from the many tanker spills could theoretically cover one-third of the entire surface of the ocean (Kalmakov and Tkalin 1986). Additionally, because the discharge is usually localized to the vicinity of the accident, the potential for damage to coastal and shelf resources is considerable (Kalmakov and Tkalin 1986). The breakup of the supertanker *Amoco Cadiz* impacted France's coast by causing $75 million in damage to marine resources (Gundlach et al. 1983). Full impact of the spill from the *Exxon Valdez* into Alaska's Prince William Sound is yet to be determined (Anon. 1989).

Although marine oil pollution spreads primarily by ocean currents, long-distance atmospheric transfers of petroleum hydrocarbons can contaminate open areas of the World Ocean. This contamination is connected with the evaporation and incomplete combustion of gasoline, kerosene, and other light petroleum fractions (Pane and Phillips 1985).

Ocean concentrations of petroleum hydrocarbons vary widely. Much petroleum remains on the surface microlayer in the form of aggregates of various sizes (Norton and Franklin 1980; Atlas et al. 1981). In the waters of the Northwest and Southwest Pacific Ocean, the concentration of petroleum hydrocarbons varies from 0 to 200 μg/L; in the Northeast Atlantic Ocean, from 0 to 160 μg/L; in the North Sea, from 0 to 350 μg/L; and in the Mediterranean Sea, from 0 to 950 μg/L (Izrael and Tsyban 1981). In the sea-surface microlayer, hydrocarbons and other contaminants are enriched by 10^2 to 10^4 times the concentrations found in the water column (Hardy 1982; Kalamov and Tkalin 1986). Perhaps the surface microlayers are at greatest risk from global pollution (Tsyban 1971).

The diverse populations of marine microorganisms have the capacity to degrade many of these materials in time. An example of the adaptability of marine microorganisms is the recent discovery of hydrocarbon seep communities (Brooks et al. 1987). However, petroleum hydrocarbons may present a great threat to the Arctic and Antarctic regions, where they may accumulate due to the low rate of biodegradation and low nutrient availability (Atlas 1986). In addition to high-latitude spills, approximately 30,000-40,000 t of petroleum products are carried into the Arctic Ocean annually by the North Atlantic Current (Simonov 1983).

Industrial Discharges into the World Ocean

The disposal of waste from industrial activities has been accelerating over the last several decades in a number of ocean regions. The ecological consequences of this type of activity have not been intensively studied and could have significant adverse effects on global marine resources.

At present, more than 30,000 different chemical compounds totaling 1.2 billion metric tons are being dumped into the ocean every year (Izrael and Tsyban 1986). Among these pollutants, those presenting the greatest danger are petroleum, chlorinated hydrocarbons (pesticides, polychlorinated naphthalenes, and polychlorinated biphenyls or PCB's), and toxic metals such as mercury, cadmium, and lead (Izrael et al. 1981). Dilution, together with biogeochemical processes, will somewhat mitigate the effects of contaminants on marine ecosystems. However the belief that water in the open ocean has not experienced any adverse anthropogenic effects (GESAMP 1982) is based on poor data and poor assumptions (Bennet and Davis 1985) and does not agree with results observed over the past few years. The case can be made that pollution problems exist for the Northwest Atlantic Ocean (Sears et al. 1985), north and central regions of the Pacific Ocean (Donat et al. 1986), Indian Ocean, and in other open areas of the World Ocean (Moiseeva 1985).

The presence of polycyclic aromatic hydrocarbons (PAH's), a class of compounds with demonstrable toxic, mutagenic, and carcinogenic effects in the ocean is primarily attributable to anthropogenic activities. Among the major sources of PAH's reaching the biosphere are atmospheric deposition of incompletely burned hydrocarbons (50,000 t), petroleum spillage from transportation accidents (170,000 t), waste water from urban centers (4,400 t), and surface runoff from land (2,700 t). In contrast, natural processes such as volcanism, microbial biosynthesis, low-temperature pyrolysis, and forest and prairie fires may introduce approximately 20,000 t of PAH's into the environment (Andryukov and Nazarov 1982; Eisler 1987).

Currently, PAH's are found in many marine environments stretching from the Arctic to the Antarctic (Mallet and Perdian 1963; Clark and Law 1981). Thus, the concentration of benzo(a)pyrene (natural level of benzo(a)-pyrene in water 0.001 ppb) ranges from 0.02 to 0.50 ppb in the Baltic Sea, from 0.005 to 0.034 ppb in the Bering Sea, and from 0.005 to 0.034 ppb in the North Atlantic Ocean (Tsyban et al. 1980; Izrael and Tsyban 1983). The North Atlantic Ocean seems to be the major recipient for benzo(a)pyrene because of its proximity to industrialized nations (Tsyban et al. 1985c).

Another class of industrial compounds, polychlorinated biphenyls (PCB's), pose similar threats to global marine ecosystems. Approximately 230,000 metric tons of the estimated 370,000 metric tons of PCB's discharged into the environment enter the ocean (Tanabe 1982). As a result, no region of the World Ocean is spared contamination. For the North Atlantic, levels of PCB's range from 0.15 to 0.80 ppb, while in the South Atlantic the levels are from 0.3 to 3.7 ppb. PCB contamination is evident in the Pacific Ocean (0.04-1.1 ppb), the Bering Sea (0.07-0.13 ppb), the Indian Ocean (0.04-0.07 ppb), and the Antarctic Ocean (0.04-0.07 ppb) (Fedoseyeva and Khesina 1968; Chumichyov 1974; Erhard and Sejuene 1985; Fedoseyev and Plakotnik 1985). This accumulation of PCB's in the remote regions of the World Ocean, far from sources of production and utilization in the northern hemisphere, illustrates the tight coupling of terrestrial and marine ecosystems through global transport processes. If current trends continue, the levels of PCB's (and chlorinated hydrocarbons, in general) in the World Ocean may increase 1.5-1.7 times by the year 2000 (Fedoseyev and Plakotnik 1985).

As we have seen from this brief discussion, chronic pollutants tend to be distributed to the open ocean through oceanic processes that promote the spread of contaminants globally. Chlorinated hydrocarbons are now appearing in remote portions of the ocean. Their extensive distribution, their stability and potential for bioaccumulation, their high toxicity, and their pronounced mutagenic effects make chronic, sublethal exposure to low levels of these contaminants a serious ecotoxicological problem to marine ecosystems.

With each new year, new contaminants, such as polychlorinated dibenzodioxins, dibenzodioxins, polychlorinated dibenzofurans (PCDF) and polychlorinated camphenes (toxaphene) are discovered in the World Ocean. These compounds, which bio-accumulate and are highly toxic, may have an adverse impact on the processes of biochemical cycles of vital elements. New analytical methods are needed to detect these compounds in the marine environment.

The Flux of Pollutants Through Marine Food Webs

There is much more naturally occurring organic matter in the ocean (1,012 t) than any of the above organic pollutants (Gunkel and Gassman 1980). However, most of the organic pollutants, in addition to being toxic, are lipophilic in nature. Therefore, substances like PAH's and chlorinated hydrocarbons typically bioaccumulate onto marine plankton and can be

passed through marine food chains (Andelman and Suess 1973; Neff 1979; Tsyban 1985a; Tsyban et al. 1985a, 1985b). The average bioaccumulation coefficients for various chlorinated hydrocarbons are as follows: zooplankton, 6.4×10^3 for PCB and 1.2×10^4 for DDT; ichthyofauna, 1.7×10^5 for PCB and 3.1×10^5 for DDT; marine mammals 1.3×10^7 for PCB and 3.7×10^7 for DDT (Andelman and Suess 1973). Consequently, ecotoxicological effects on these critical trophic components may ultimately interfere with marine food chains.

In addition to the possible impact of these substances on fisheries, their effect on the biogeochemical role of the ocean is almost totally unknown. This latter issue is significant in that the critical role of the ocean in the cycling of such important atmospheric components as the greenhouse gasses has been recognized only recently. Broecker et al. (1979) estimated that as much as 50% of the carbon dioxide released into the atmosphere by the burning of fossil fuels has been absorbed by the ocean. In the United States, Global Ocean Flux (GOFS), a new scientific program to address this process, has been organized. Thus far, the GOFS program does not address the involvement of man-made substances other than carbon dioxide on carbon flux in the oceans.

It has been suggested that the addition of nutrients to coastal areas from municipal sewage has increased biological consumption of atmospheric carbon dioxide in the ocean (Walsh et al. 1981). However, based on the above discussion of the variety and pervasiveness of organic pollutants in the sea, the issue of the negative effects of man-made products on the biogeochemical role of the ocean may loom larger as data on the ecological effects of these substances accumulate.

Marine Debris

In addition to the dissolved substances discussed above, human activities are responsible for an increasing amount of solid debris in the ocean. Particularly troublesome in this respect are plastics whose resistance to chemical breakdown makes their rate of removal from the ocean very slow. Concentrations of surface-floating plastics have been observed to be greatest in the subtropical waters of the North Pacific and least in the more northern waters (Day and Shaw 1987). In the North Atlantic, the Sargasso Sea appears to contain the largest concentrations of plastic debris (Carpenter and Smith 1974), probably due to the confining circulation in these waters.

In addition, large amounts of plastic debris are produced from an increasingly large open-ocean drift-net fishing industry. The effects of such debris are diverse: the larger pieces entangle marine animals and birds and a variety of marine organisms can ingest the smaller pieces. Either process can lead to the death of the organism. Almost all of the reports of marine debris thus far have addressed floating materials. There are also many plastics (such as the commonly used plastic polyvinyl chloride) that sink. The impact of such debris on the ocean's benthic ecosystem has not been addressed.

Metals in the Ocean

Heavy metals are also widely distributed and dangerous ocean contaminants. One of the ways metals (including such toxic ones as mercury, lead, and cadmium) enter the ocean is through direct contamination and runoff from land (Izrael and Tsyban 1981) (see Table 1). They also reach the ocean by long-distance atmospheric transfer and precipitation onto the underlying water surface; atmospheric transfers are a main source of metal contamination in the ocean. The increased concentration of metals in the atmosphere, in turn, is caused principally by the burning of coal, petroleum, and other fossil fuels; the mining of ore; and the smelting of metals (Billings and Matson 1972). It has been estimated, for example, that

Table 1. *Anthropogenic data on the World Ocean listed according to contaminants (tons/year). (Adapted from Izrael and Tsyban 1981.)*

Contaminating substance	Natural flow	Anthro-pogenic flow	Portion of flow from anthro-pogenic causes	Flow into ocean: Direct contam-ination, flow from land	Flow into ocean: Atmospheric preci-pitation
Lead	$1.8 \circ 10^5$	$2.1 \circ 10^6$	92	$(1\text{-}20) \circ 10^5$	$(2\text{-}20) \circ 10$
Mercury	$3.0 \circ 10^3$	$7.0 \circ 10^3$	70	$(5\text{-}8) \circ 10^3$	$(2\text{-}3) \circ 10^3$
Cadmium	$1.7 \circ 10^4$	$1.7 \circ 10^4$	50	$(1\text{-}20) \circ 10^3$	$(0.5\text{-}14) \circ$
Petroleum	$6.0 \circ 10^5$	$4.4 \circ 10^6$	88	$(3\text{-}4) \circ 10^6$	$(3\text{-}5) \circ 10^5$
Chlorinated hydrocarbons: (PCB)	--	$8 \circ 10^3$	100	$(1\text{-}3) \circ 10^3$	$(5\text{-}7) \circ 10^3$
Pesticides, dibenzodioxins, dibenzoflurans	--	$1.1 \circ 10^4$	100	$(4\text{-}6) \circ 10^3$	$(3\text{-}7) \circ 10^3$

in 1966, 310,000 metric tons of lead were emitted into the atmosphere from gasoline combustion (Muruzumi et al. 1969). Lead deposition into the ocean from atmospheric precipitation now exceeds geochemical inputs of this element from river drainage (Muruzumi et al. 1969; Chow 1973; Schaule and Paterson 1981). Atmospheric precipitation of cadmium approximates the amount entering from direct drainage of land, and of mercury, about 25% of the total amount entering the ocean environment (Chester and Stoner 1974; Izrael and Tsyban 1981).

Mercury is among the most toxic of metals. Its total content in the ocean is 10 million metric tons in an average concentration of 5-100 μg/L (Olafsson 1983). The concentration of mercury is 10-40 times as high in the surface layer than in the deeper water column. In the Atlantic Ocean, for example, the concentrations of mercury in the surface layer and in the layer from 0 to 100 m equals 74-1,850 and 7-1,085 μg/L, respectively (Kulebakina and Kozlova 1985).

The cadmium content of the open ocean does not vary as much. In the South Atlantic, the concentration of cadmium is 40-170 μg/L (Duce 1980). Altogether, the ocean (based on an average concentration of 100 μg/L) contains approximately 140 million metric tons of cadmium (Bewers and Yeats 1977).

Lead is less toxic than cadmium and mercury, although it has a greater tendency to be bioaccumulated. The average concentration of lead in open ocean waters is 20-40 μg/L (Osipov et al. 1983). The maximal concentrations of lead, as with cadmium, occur in the microlayer of the ocean just below the surface (Kremling 1985; Kalamakov and Tkalin 1986). The bioaccumulation factors for these metals in planktonic organisms are lead -4.0 x 10^5, mercury -3.4 x 10^3, and cadmium -2.1 x 10^4 (Morozov and Petukhov 1981). At these elevated levels, serious genetic damage to the organisms can occur.

The contamination of the ocean by metals is becoming more and more serious. According to recent estimates, the total quantity of lead and mercury now being removed in the process of biosedimentation from the ocean surface is substantially less (1/40 to 1/30) than the amount of lead and mercury introduced into the ocean from anthropogenic and natural sources.

Current predictions are that the level of production of these contaminants will increase more than twofold by the year 2000. Moreover, it is known that global emissions of mercury and cadmium are largely determined by the combustion of organic fuels. Available data suggest that this output could double or triple by the year 2000, and increase 4-5 times by 2025 (Izrael and Tsyban 1985). It is also believed that the concentrations of these metals in the ocean will also more than double from their current levels by the year 2000.

Microbiological Contamination

Another aspect of human interaction with the ocean that may have serious human health consequences is microbiological contamination of the marine environment from the dumping of untreated commercial and residential sewage into the sea. Pathogenic and marginally pathogenic microorganisms entering the sea through drainage may adapt to their new surroundings. In organically polluted water, microorganisms are not only capable of surviving over long periods of time, but also of reproducing. These microbes can be transferred as aerosols through the atmosphere to the mainland, as well as to the open waters of the ocean (Berga and McLeod 1976; Roper and Marshall 1979; Labelle 1980).

Many pathogenic microorganisms accumulate and develop actively in filter-feeding organisms of ecological and economic significance (e.g., bivalve mollusks, oysters, and mussels). Recent research has established that intestinal microflora are distributed in open regions of certain seas (Chumichyov 1974). These microorganisms can also undergo active development in bacterial neuston in the interface layer between the sea and the atmosphere (Tsyban 1985).

Increased human coastal populations in the last few years have been associated with intensive eutrophication of inland seas and coastal regions of the ocean. This augmented primary biological production is the outcome of greatly increased sewage nutrient additions (primarily from commercial-residential, stream, and industrial drainage). These substances can be used directly for biological production and are easily degradable into their constituent elements (phosphorous and nitrogen), which are then used to fuel increased production.

Today, the eutrophication of the marine environment is present even in several pelagic zones of the Pacific Ocean, a result of atmospheric transfer of bioactive elements and suspended organic substances.

The ecological consequences of ocean contamination are now being studied primarily for coastal regions and inland and partially landlocked seas. At the same time, adverse ecological impacts can be expected for open-ocean ecosystems. Marine organisms, finely adapted to the constancy of their surrounding environment, may be especially sensitive to chronic low doses of toxicants (Nelson-Smith 1977). Pelagic ecosystems may have lower resistance and greater sensitivity to contamination than coastal areas. Upwelling ecosystems and polar ecosystems where the activity of biodegradation is greatly reduced may also be significantly at risk.

Many oceanic systems are now being exposed to the influence of so-called "factors of small intensity," that is, low doses of toxicants. Stable, long-lived compounds enter the biological food web and are actively accumulated by marine organisms. The long-term influence of low concentrations of molecularly stable compounds having mutagenic and toxic effects can lead to marked damage in the life processes of living organisms. Furthermore, the functioning of open ocean ecosystems is damaged by a chain of successive reactions. Such destruction is difficult to discover at the early stages of adverse effect because natural ecosystems adapt themselves in the course of evolution to the natural variability of environmental factors. However, as small "disturbances" accumulate, an ecosystem can

move beyond the bounds of stability and cross over into a new mode of behavior. Such tendencies can be determined through long-term observation of planktonic communities, together with research in marine ecosystem dynamics (Izrael and Tsyban 1986).

Current research indicates that the more polluted the natural environment becomes, the greater the frequency of dangerous mutations for the individual organisms. The increased rate of mutagenesis is linked with exposure to specific mutagens, and this exposure may have one of several outcomes. In populations with short generation times and high production, genetic adaptation that can produce new cell lines capable of metabolizing human generated chemicals is possible. This is the basis for the Soviet monitoring program for ocean organisms indicative of certain pollutants. On the other hand, when there is a long life span and small number of offspring, the increase in mutations in response to the presence of mutagens in the marine environment almost always leads to a population decrease (Zasykhina 1979; Dubinin 1981).

Many pollutants are carcinogenic in nature. In addition, Soviet research has found that certain microorganisms (Albright and Wilson 1974; Karpinsky and Rosenkranz 1981) excrete carcinogens in the presence of mutagenic substances (Lindmark 1981; Bandrau et al. 1984; Chugh and Kardi 1985; Jamagata et al. 1985; Schoeny et al. 1985). Therefore, under the influence of mutagens in the environment, cell lines that are capable of producing still more carcinogenic compounds may appear. As a result of this synergistic influence, the biological effects of certain contaminants in open regions of ocean would be amplified even though their ambient concentrations do not exceed 10 $\mu g/L$ or, in rare cases, 100 $\mu g/L$ (Gerlakh 1985).

The possible biological intensification of pollutant effects discussed above greatly complicates the problem of setting "safe" lower levels for mutagens in the environment. The Soviet phase for such effects is "factors of small intensity." This situation should be considered in controlling genetic consequences of contamination of the ocean.

Thus, changes in the chemical composition of the ocean can bring about not only the destruction of the structure and function of the ecosystem, but also damage to the gene pool of marine organisms. However, our knowledge about the most important ecological phenomena in the open ocean (trends of planktonic communities, production-destruction processes, biochemical cycles of contaminants, etc.) is limited by insufficient information. This makes it difficult to predict the ecological effects of marine pollution and to prescribe measures that will be effective against it.

Moreover, as anthropogenic influence on the ocean becomes progressively greater, the implementation of effective measures to preserve its biological resources becomes more important. Here, a unified approach to the ecological analysis of the ocean is needed. Long-term observations would help unravel the anthropogenic effects from the underlying natural variability of marine biological processes.

Certain regions of the ocean need much more extensive sampling; one result of this work would be to create a global data bank that can keep track of the pollutant effects in the marine ecosystem. These data should include measurements on the physical, geochemical, and hydrobiological processes occurring in the ocean, as well as the ecophysiological conditions of marine organisms in impacted and baseline regions of the ocean (Bennet and Davis 1985).

Summary

The following are the major results of international research on the current ecological situation in the World Ocean.

1) Pollutants are transported by ocean currents over great distances from their points of entry. Thus, open areas of the

ocean are increasingly exposed to anthropogenic contamination. Some of the most vulnerable ecosystems in the marine environment appear to be cold-water systems, coral reef ecosystems, and upwelling ecosystems.

2) Areas of chronic contamination have been found where heterogeneous water masses converge, in estuaries, and in areas of restricted circulation. These regions and other fragile ecosystems can be conditionally considered ecologically stressed zones of the World Ocean.

3) Long-distance atmospheric transfer of contaminants into the ocean is occurring. The atmosphere is a carrier of many chemical compounds such as suspended and dissolved substances, biogenic elements, and metals. Borne by atmospheric currents, contaminated substances drift thousands of kilometers to the most remote areas of the ocean.

4) Each year, the following substances are deposited onto the surface of the ocean: 3×10^5 t of petroleum hydrocarbons, 2.0×10^5 to 2.0×10^6 t of lead, 2.0×10^3 to 3.0×10^3 t of mercury, 5.0×10^2 to 1.4×10^4 t of cadmium, 2.0×10^3 to 3.0×10^3 t of polychlorinated biphenyls (PCB's), and 1.0×10^3 to 3.0×10^4 t of arsenic (Duce 1980; Duce et al. 1980).

5) Pollutants are rapidly transferred from the surface waters into the deeper layers of the ocean by the biological processes occurring in the plankton. The extent to which these substances are accumulated in the marine biota and are interfering with plankton processes are currently unknown.

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FLUXES AND ASSIMILATIVE CAPACITY AS CHARACTERISTICS OF MARINE ECOSYSTEMS

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Introduction

As the variety and amount of pollutants that find their way into the sea increase, so has concern about the effect of these increases on marine life. One conceptual model that has been proposed to aid in the analysis of anthropogenic effects in the ocean is that of assimilative capacity (Izrael and Tsyban 1986). Broadly defined, assimilative capacity is the maximum amount of contaminants that can be accommodated by the marine system before the system shows signs of disturbance. Obviously, this concept covers many processes; a marine system can accommodate substances by accumulation, destruction, transformation, or transport. Just as obviously, the determination of environmental disturbance is not yet an exact science.

This chapter addresses the common ground between the United States and the Union of Socialist Soviet Republics regarding the concept of assimilative capacity and is not intended as a review of all relevant work in this area in the two countries. As will become apparent, assimilative capacity is an attribute of the highest level of system organization–that of the ecosystem. Like the marine ecosystem itself, it can be broken down into physical, chemical, and biological components, and so encompasses much of what is considered modern oceanography. Instead of an interdisciplinary review, this paper focuses on the U.S. approach to the study of pollutants in the ocean, and how this approach compares to the concept of assimilative capacity.

Marine Biogeochemistry and Assimilative Capacity

Numerous terms and concepts currently in use in Soviet and American environmental science also apply to the analysis of contaminant substances in the sea. Therefore, a brief review of the terms used in the present discussion is warranted. In the United States, the cycling of materials through the environment is the subject of a relatively new field of study known as biogeochemistry. The name explicitly recognizes the interdisciplinary nature of material flow, in that typically, the

biochemical changes are superimposed on preexisting geochemical cycles.

Much work in the United States has been devoted to understanding the various elemental cycles in the sea. One useful categorization is to segregate the numerous elements present in seawater on the basis of their interaction with ocean biology into bio-limiting, bio-intermediate, and bio-unlimiting elements (Broecker and Peng 1982). These categories reflect the relative degree to which the various elements are consumed in surface waters. For example, bio-limiting elements such as nitrogen and phosphorus can be completely removed from surface water by biological production, so that their availability influences the trophic status of the plankton community. Bio-unlimiting elements, on the other hand, are not influenced significantly by biological activity and show little variation from place to place. As more chemical measurements accumulate, however, it appears that there are actually few elements in seawater that do not display some depth variation indicative of biological influence (Quinby-Hunt and Turekian 1983).

Several concepts from the foregoing geochemical analysis are relevant to the concept of assimilative capacity. This will be illustrated by the following analysis taken largely from Broecker and Peng (1982), but modified to allow for the in situ destruction of man-made substances. Consider a simplified ocean that is composed of only two distinct physical compartments: the warm surface layer and the cold bottom waters. The surface ocean has some input of a pollutant, I (mass/time). The rate of removal of this substance from surface water depends on three basic mechanisms: (1) the amount of surface-water downwelling (V_m) and the surface concentration of the substance (C_i); (2) the downward flux of particulate material that contains the substance (F_i); and (3) the destruction or transformation of the in situ (D_i). Therefore, at steady state:

$$I = (V_m * C_i) + F_i + D_i \quad (1)$$

On the basis of this simple mass balance, the relative importance of the different removal mechanisms can be determined for the various man-made substances. For example, the fraction of I removed by particle flux can be estimated from:

$$[I - (V_m * C_i) - D_i] / I \qquad (2)$$

Likewise, the fraction of I removed by in situ processes can be estimated from:

$$[I - (V_m * C_i) - F_i] / I \qquad (3)$$

The dominant removal mechanism will vary among contaminants. For chemically resistant, hydrophobic substances such as polychlorinated biphenyls (PCB's), the fraction removed by particle flux (equation 2) would dominate (Geschwend and Shian-Chee 1985). Conversely, for more labile substances such as the low carbon number polyaromatic hydrocarbons (PAH's), in situ degradation mechanisms (equation 3) would probably dominate.

The analysis above can also be extended to cover the amount of the substance removed from bottom water by burial in the sediments. If all the loss processes and their rates are known, the turnover time of a surface seawater contaminant can be calculated as the ratio of the total amount of the man-made substance in the ocean (mass) to the total loss rate (mass/time). The longer this turnover time, the longer the biological systems in the ocean will be exposed to that specific man-made substance. On the basis of turnover time, man-made contaminants can be categorized into one of two categories: acute or chronic. Those having relatively short (less than a year) turnover times are in the acute category; the longer-lived contaminants are in the chronic category.

Most of the biogeochemical work thus far has concentrated on elemental cycling and has not addressed the movement of pollutants. However, the substantial conceptual basis that already exists (and is briefly outlined above) is

a useful approach for the analysis of assimilative capacity of the oceans for man-made substances as well.

Assimilative Capacity as a General Concept

There is no a priori reason to restrict the analysis of the ocean's assimilative capacity to toxic substances. Human activities also augment the flux of a variety of naturally occurring nutrient substances into the sea. These include phosphate (from sewage), nitrate (from sewage and acid rain), and carbon dioxide (largely from the combustion of fossil fuels). Like toxic contaminants, increased nontoxic substances may also cause direct negative effects in the marine environment. For example, nutrient additions can directly change the trophic status of affected coastal areas. This has already occurred in coastal areas near large urban centers (Walsh 1983). The increased biological and chemical oxygen debts caused by eutrophication in coastal areas can produce anoxic conditions and lead to fish and shellfish kills. Also, an increase in oceanic carbon dioxide will change the dissolution equilibria of calcium carbonate, and this may ultimately affect marine organisms that use calcium carbonate in construction of hard parts.

Almost wholly unexplored is the interaction between toxic and nontoxic substances in the sea. It is likely that the assimilative capacity of the ocean for nontoxic man-made substances will be negatively affected by the simultaneous addition of toxic substances. In effect, toxic substances alter the nature of the biological transformation by inhibiting or destroying critical populations (Stoecker et al. 1986). This effect complicates the analysis of assimilative capacity because it changes the character of the biological system itself.

Little understood, as well, are the indirect biological effects of the end products of human activities. For example, the depletion of ozone in polar regions in recent years is attributed largely to the addition of chlorofluorocarbons to the atmosphere. It is not clear what biological effects the increased ultraviolet radiation reaching the ocean's surface may have. Concern about the effects of the recent rapid increase in atmospheric carbon dioxide is also growing (Fig. 1). This increase, mainly from human activities, in particular the burning of fossil fuels, may produce a warming of the Earth's climate (MacCracken 1983) that would also affect the biology of the oceans, perhaps to a significant degree. Neither chlorofluorocarbons nor human-made carbon dioxide are themselves toxic to marine ecosystems. Instead, any deleterious effects on marine ecosystems will be through atmospheric heat and radiation changes. Therefore, the impact of these indirect effects of contaminant substances on marine life depends on factors outside the ocean itself. The nature of such large-scale problems illustrates the need for interdisciplinary study on a scale that has not yet been undertaken.

The U.S. Global Ocean Flux Program

A simplified view of the major parts of the global carbon system and the approximate fluxes of carbon among them is presented in Fig. 2. Although 88 X 10^{15} g of carbon have been released to the atmosphere from fossil fuels, only 53 X 10^{15} g have accumulated in the atmosphere (Watts 1982). This discrepancy has been attributed to the role of the oceans as a sink for atmospheric carbon dioxide (Broecker et al. 1979). In the United States, the Global Ocean Flux (GOFS) program was started to determine the degree to which the ocean serves as a sink for atmospheric carbon dioxide by the process of particulate flux of organic matter from surface water. Interdisciplinary field studies began in GOFS during 1989.

Particle formation and flux is a critical process in the removal of substances from surface ocean waters. This is true for carbon dioxide as well as for more exotic substances from the ocean surface. Therefore, the general goals and approach of the GOFS program is

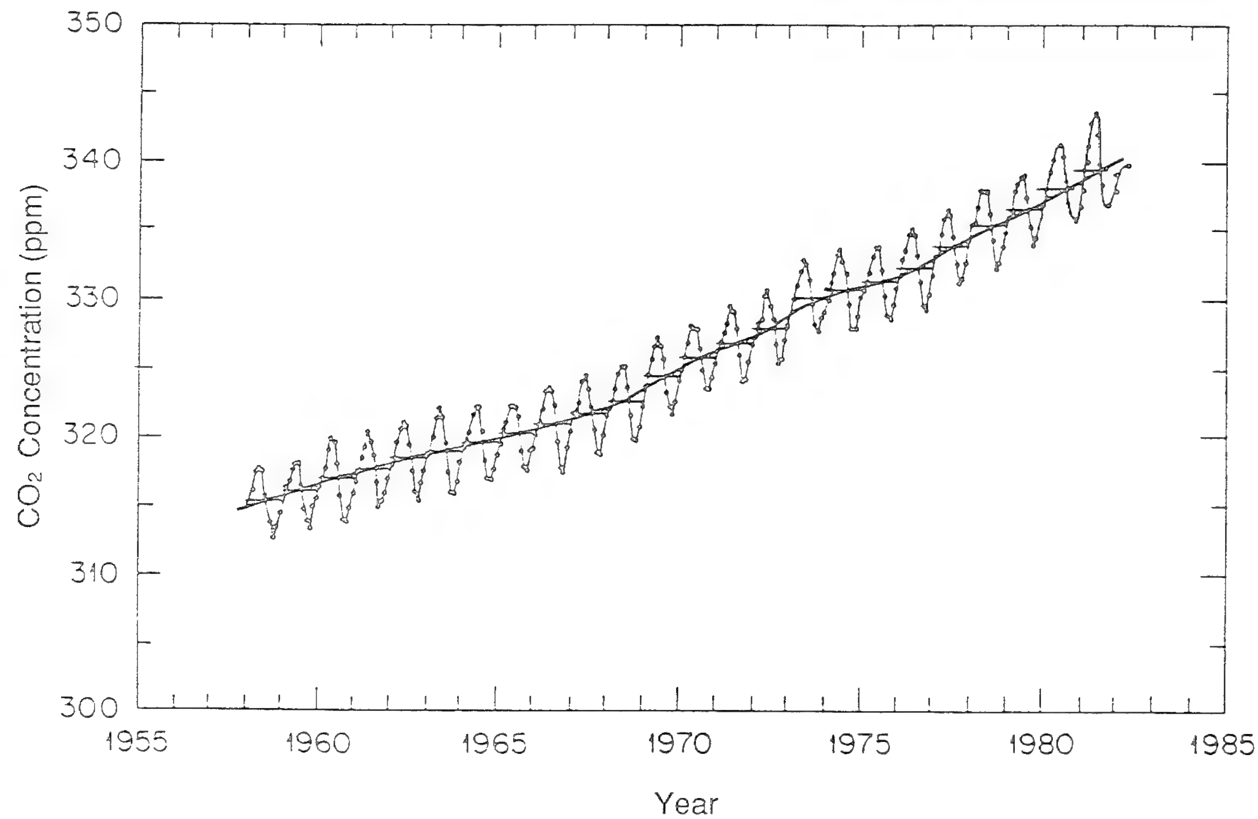

Fig. 1. The increase in atmospheric carbon dioxide observed at Mauna Loa Observatory, Hawaii from 1959 through 1982 (Keeling et al. 1976, 1982). The atmospheric concentration increase in carbon dioxide corresponds to a net increase of 53 X 10^{15} g of carbon.

relevant to the analysis of the assimilative capacity of most ocean surface contaminants. Although the U.S. GOFS program is not designed to assess the environmental consequences of the fossil-fuel carbon dioxide additions to marine ecosystems, the similarities between the GOFS analysis of carbon flux and the question of assimilative capacity in the IGOM program are striking. Thus, a brief review of the GOFS program follows that summarizes the approach to interdisciplinary marine environmental work taken in the United States.

The GOFS program is dependent upon detailed physical analysis of the ocean basins. This work will not be done as part of GOFS itself. Instead, physical data and models from the World Ocean Circulation Experiment (WOCE) will be used in the GOFS analysis. Two of the most important goals of GOFS are (1) to develop the capability to estimate primary production on a global scale using remotely sensed properties of the surface layer, and (2) based on objective 1 to define the variability of particulate organic matter export from the upper ocean. Although simple mixing of inorganic carbon between the deep and surface layers of the ocean has a significant impact on atmospheric exchange, ocean biology is also a major factor in the flux of carbon through the ocean. Biological processes consume inorganic carbon in surface water, as well as transform and transport this carbon to deeper water. These are the same processes

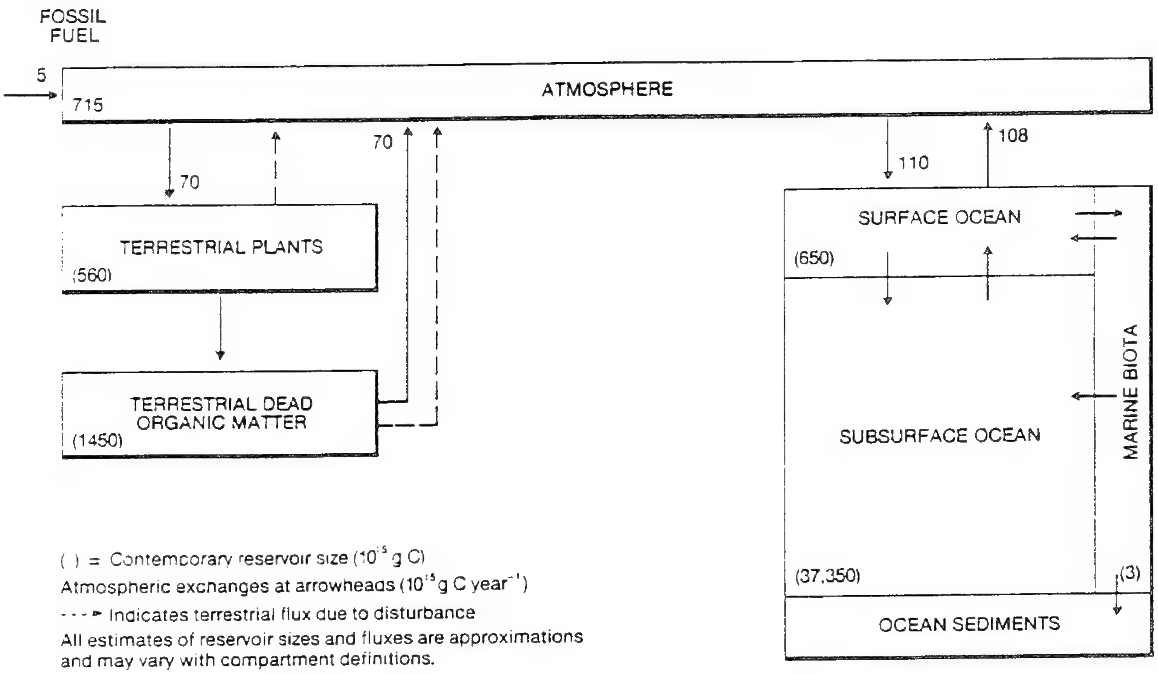

Fig. 2. The actively exchanging components of the global carbon cycle and the estimated reservoir sizes and fluxes between them (Dahlman 1984).

that must be considered for any contaminant introduced to the marine environment.

In GOFS, these biological components have been grouped into two general categories: upper ocean processes and benthic studies. The upper ocean processes, in turn, are composed of detailed chemistry, biology, and sediment-trap studies. One of the core concepts in the analysis of carbon flux from surface waters is that of new production (Dugdale and Goering 1967). New production is a subset of total production and, in theory, defines the amount of organic matter that can be exported from surface water at steady state. Therefore, the concept of new production has been tested extensively in conjunction with sediment-trap studies that measure the particulate export from surface waters. In general, the curvilinear relationship between new production and particle export predicted by Eppley and Peterson (1979) appears to be robust. Seasonal sediment trap studies indicate that maxima in particle flux coincide with spring bloom periods in which new production is greatest (Fig. 3).

However, not all the particulate material formed in surface water is exported to deeper water. There is an intense rate of biological

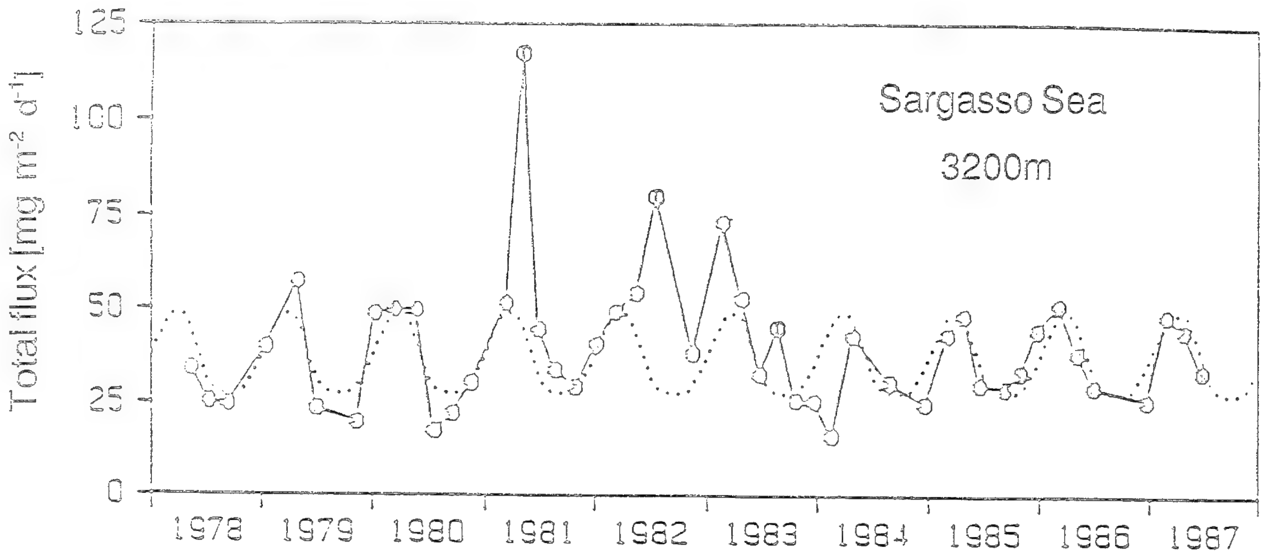

Fig. 3. A 10-year record of total particle flux collected in sediment traps in the Sargasso Sea (Deuser 1986).

recycling among the various planktonic groups. The surface water biological recycling transformations are often analyzed in terms of a nitrogen mass balance (Fig. 4), because the new production concept is based on the marine nitrogen cycle. Groups such as protozoans and microflagellates are now thought to be very active in consuming surface particles. The food web composed of these small consumers and their bacterial and smaller phytoplankton prey is known as the microbial loop (Azam et al. 1983). Much of the organic material is lost from particulate material (Fig. 4) either in the process of feeding or in respiratory losses, because the transfer efficiency between trophic levels is significantly less than one. Presumably, this would release some of the pollutants back to the water as well.

The fate of pollutants in surface waters is not the only determinant of assimilative capacity. Significant biological interactions can occur in deeper waters, and so the fate of organic material (and any associated pollutants) as it moves into deeper waters must be considered. A large component of GOFS will examine carbon flux in deep-basin water and the benthos. Beneath the surface layer, the amount of particulate organic material decreases rapidly with depth (Fig. 5). Thus, due to respiratory losses, only a small fraction of the surface organic production reaches the sea floor.

In the GOFS benthic studies, the regeneration and burial fluxes at selected transect sites will be measured. The amount of material reaching the sea floor is much less than the surface flux. However, the burial of this material in sediments results in the longest term isolation from the environment. Previous sampling indicates that this benthic flux varies a great deal spatially and appears to be associated with the overlying productivity. For example, the elevated benthic flux along 140°W longitude near the equator (Fig. 6) probably reflects the intense surface productivity associated with equatorial upwelling regions.

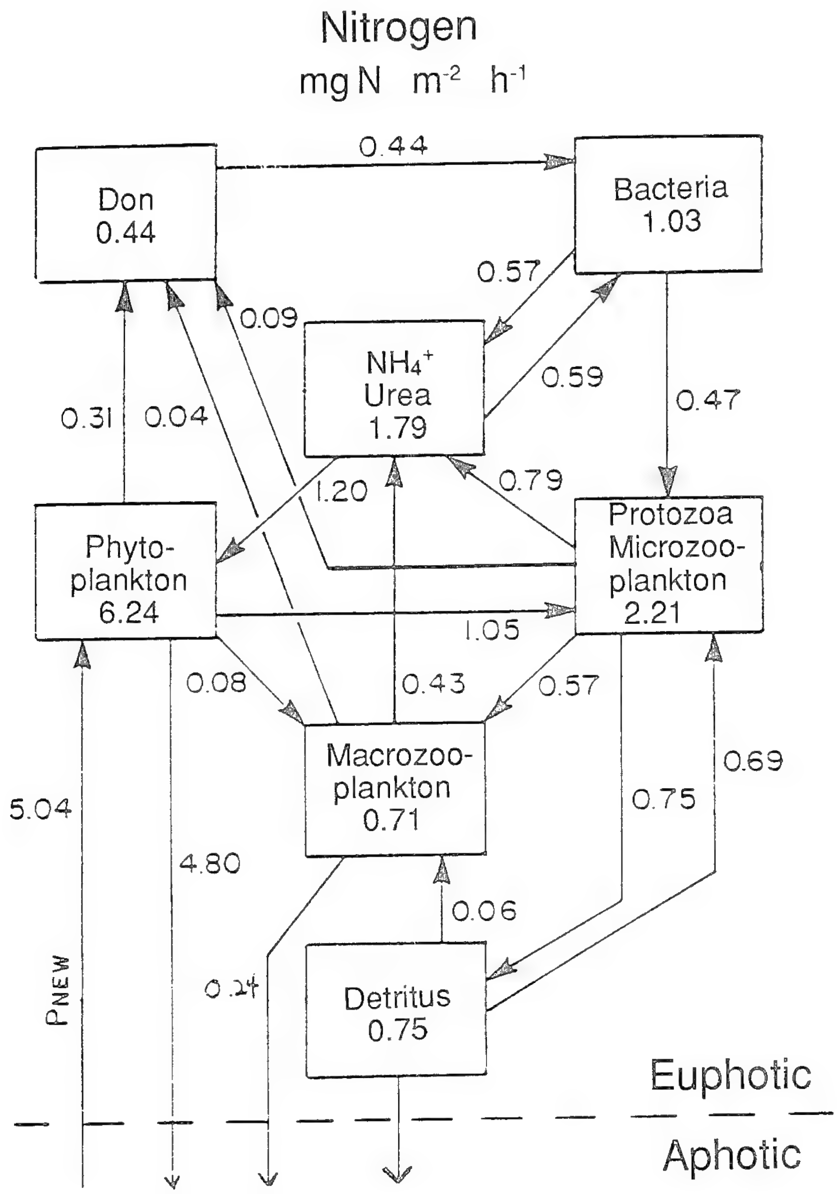

Fig. 4. Schematic interpretation of biological nitrogen flow in the surface waters of a North Atlantic Warm Core Ring (from Ducklow et al. 1988). Note the dominance of phytoplankton sinking as a removal process for surface ocean organic nitrogen.

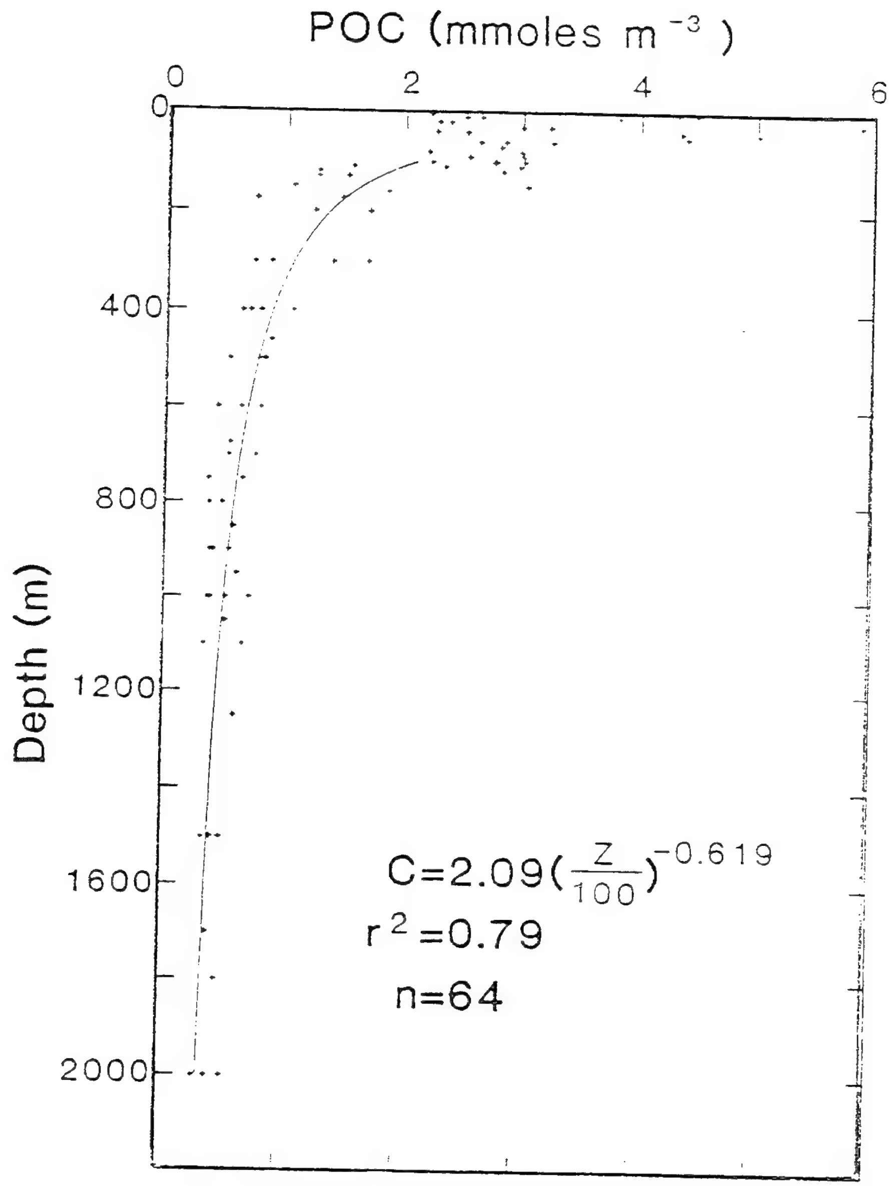

Fig. 5. The depth distribution of particulate organic carbon (a composite of four stations in the northeast Pacific from Martin et al. 1987).

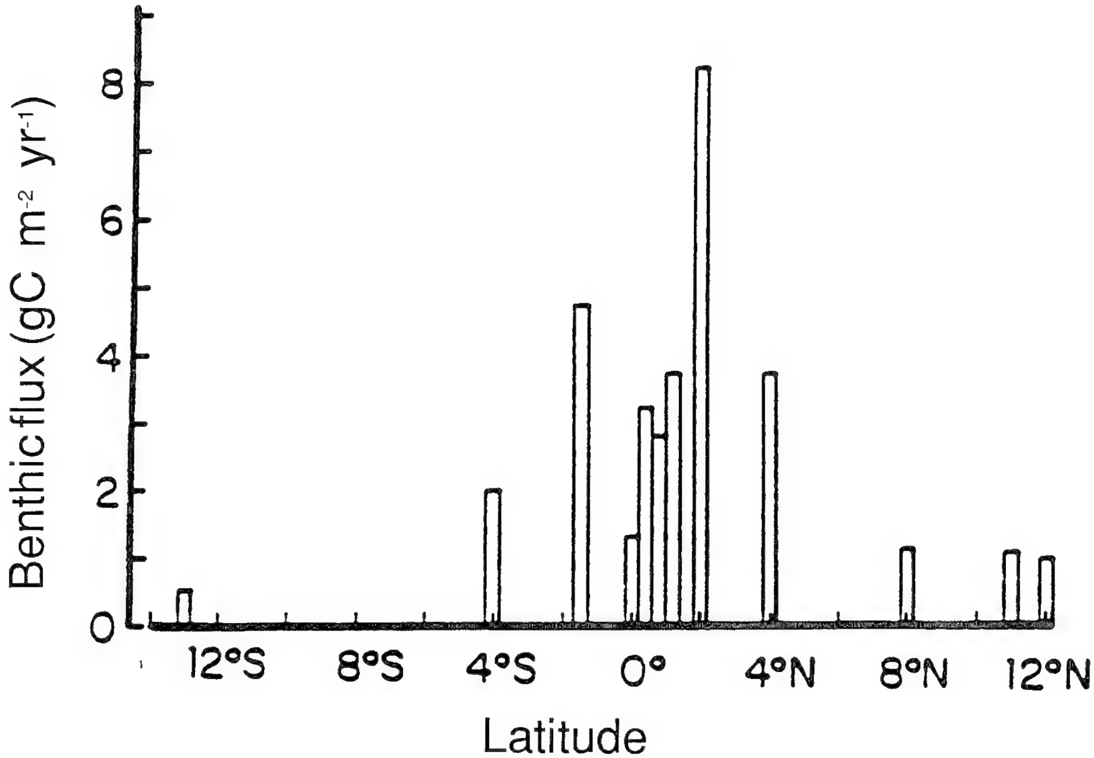

Fig. 6. The latitudinal variation in the benthic flux of organic carbon along 140 degrees west longitude (from Bender et al. 1987).

Also, the respiration occurring in ocean sediments below 2.5 km may exceed the respiration occurring in situ (Fig. 7). Clearly, more data of this type need to be collected to assess these estimates more accurately.

Most of the previous discussion has centered on the deeper ocean areas. Because of their vast geographic area, these areas are certainly a major factor in the assimilative capacity of theoceans. However, the coastal margins may play an equally large role (Walsh 1983). This view is supported by the fact that the ocean margins are generally the most biologically active areas of the world ocean and are also the areas that receive the greatest amounts of many substances. This latter fact makes continental margins the front line in the assimilative capacity of the oceans for man-made substances.

The several distinct parts of the GOFS program--upper water, deep water and benthic processes, and ocean margins--illustrate the

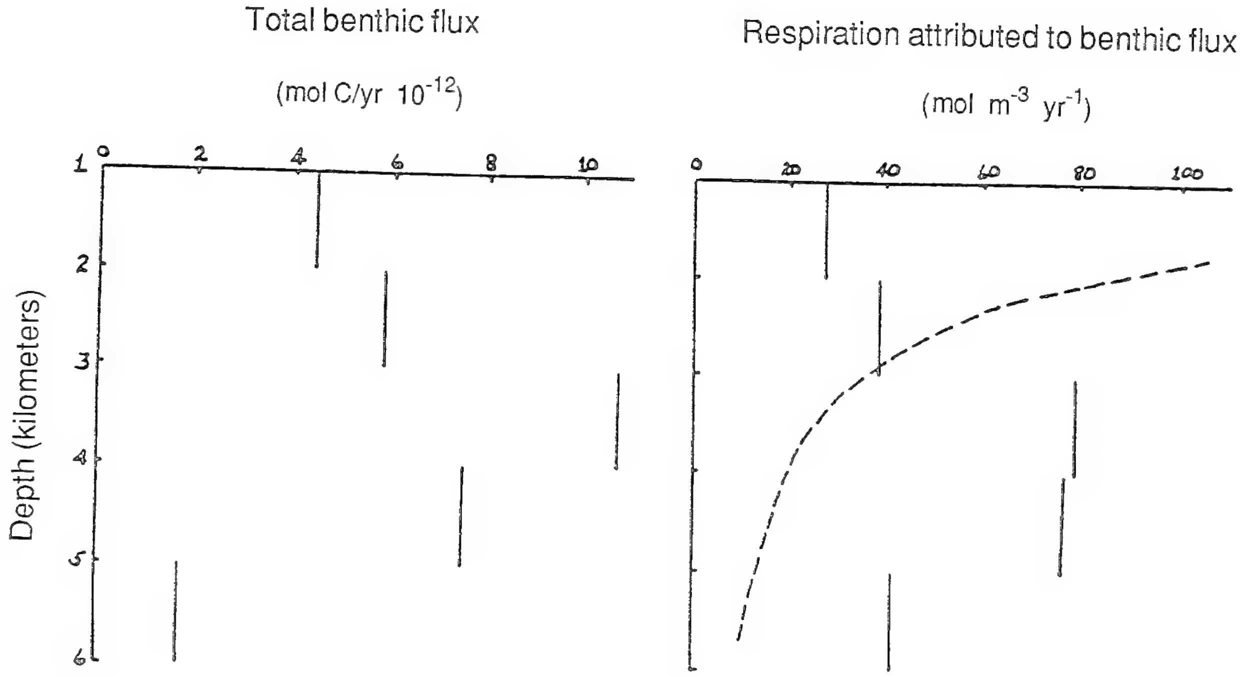

Fig. 7. Benthic oxidation rate of organic carbon in the Pacific Ocean calculated for 1-km depth intervals, and its estimated contribution to water strata in the Pacific Ocean (Bender et al. 1987). For comparison, the respiratory flux estimated from the surface productivity relationship derived by Suess (1980) is included as a dashed line.

complexity of determining the assimilative capacity of the oceans quantitatively. The GOFS program will apply a modeling approach to deal with this complexity. The increasing availability of computational resources has advanced the numerical modeling of environmentalsystems greatly in recent years. In GOFS, the modeling tools used will be both one dimensional and multidimensional. In the one-dimensional models, process studies relating biological, chemical, and particle cycling will be used to examine in detail the interaction of these processes in relation to field measurements.

Three-dimensional modeling will be used to estimate total ocean processes such as gas exchange, particle flux, and primary production.

This latter parameter will be tied closely to the remote sensing (via satellite) of global ocean plant-pigment values. At this time, there is a great deal of effort directed to modeling ocean productivity from satellite measurements of chlorophyll. The success of this effort would greatly benefit fisheries as well as assimilation studies. Remote sensing can produce a synoptic view of ocean conditions and thus provide a global data set that cannot be produced by any other means.

Summary

A quantitative assessment of the assimilative capacity of the ocean for man-made substances involves a multidisciplinary and integrated study of ocean processes. The previous discussion briefly outlined how such a study has been approached in the U.S. The processes common to both U.S. and IGOM programs are biological particle formation, transformation, and flux. These processes will have to be quantitatively known to assess the assimilation of substances by the ocean. Contaminants that adhere or concentrate on particles, such as PAH's, PCB's, or other hydrophobic pollutants, will be rapidly stripped from the water by this flux of material. Therefore, the spatial and seasonal variability in particle flux will largely determine the residence times of hydrophobic pollutants in surface waters, an important parameter in biogeochemical analysis that was discussed previously. The negative ecological effects of pollutants on surface waters may vary in a manner similar to their residence times. The global scale of these processes will require increased international cooperation in both sample collection and ecological analysis.

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Physical Oceanography

PHYSICAL CONDITIONS

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The Second Joint U.S-U.S.S.R. Expedition to the Bering Sea took place during July 1984, the time of maximum seasonal heating. Basic measurements were undertaken at four polygons arranged as shown in Fig. 1: one in the center of Bowers Basin in the south-central region (south, stations 1-3, 25, and 26); one in the west straddling Shirshov Ridge (west, stations 21-24); one near Zhemchug Canyon over the continental slope of the eastern shelf (east, stations 5-9); and one southwest of St. Lawrence Island (north, stations 13, 15-17). A few additional stations were occupied in transit across the basin and on the northern shelf. Weather during the cruise was mild. Moderately strong winds were encountered only on 3-4 July during occupation of the south polygon; on other days light winds prevailed, and only occasional patchy fog was encountered.

The conductivity, temperature, and density (CTD) instrument did not function properly; therefore, the only data on physical conditions are sea temperatures from 0 to 200 m from expendable bathythermographs (XBT's) made during each station occupation. Nevertheless, we can interpret something of the water masses encountered at each polygon.

Figure 2 depicts the general features of the temperature structure encountered at the diverse locations around the sea, illustrating the differences among the polygons, with plots of temperature at the center station of each polygon. Everywhere there was a relatively thin isothermal surface layer <50 m thick, and in the majority of cases <25 m thick, overlying a strong thermocline. The layer was thicker and the strength of the thermocline less in waters directly connected with deep basin conditions (south and east polygons). There, the upper layer was 20-35 m thick and temperatures were 6°C to 7°C, decreasing to about 4°C at 50 m. Temperatures of the subsurface layer (about 100 to 300 m) of the open Bering Sea and North Pacific in general lie between 3°C and 4°C, demonstrating that the upper layers at the south polygon (station 3) have direct and immediate connection with North Pacific water, and those at the east polygon (station 6) are part of the Bering Slope Current carrying Alaska Stream/Bering water (Coachman and Charnell 1979).

Where waters had direct connection with shelf conditions (north and west polygons), the surface layer was thinner (10-15 m), temperatures a little higher (about 7°C), and the water beneath the thermocline markedly colder. The basic reason for the differences from open ocean conditions is the degree of salinity contrast between surface and subsurface layers; the vertical salinity (and hence density) difference is much less at open-ocean stations than at shelf stations, which have fresher upper

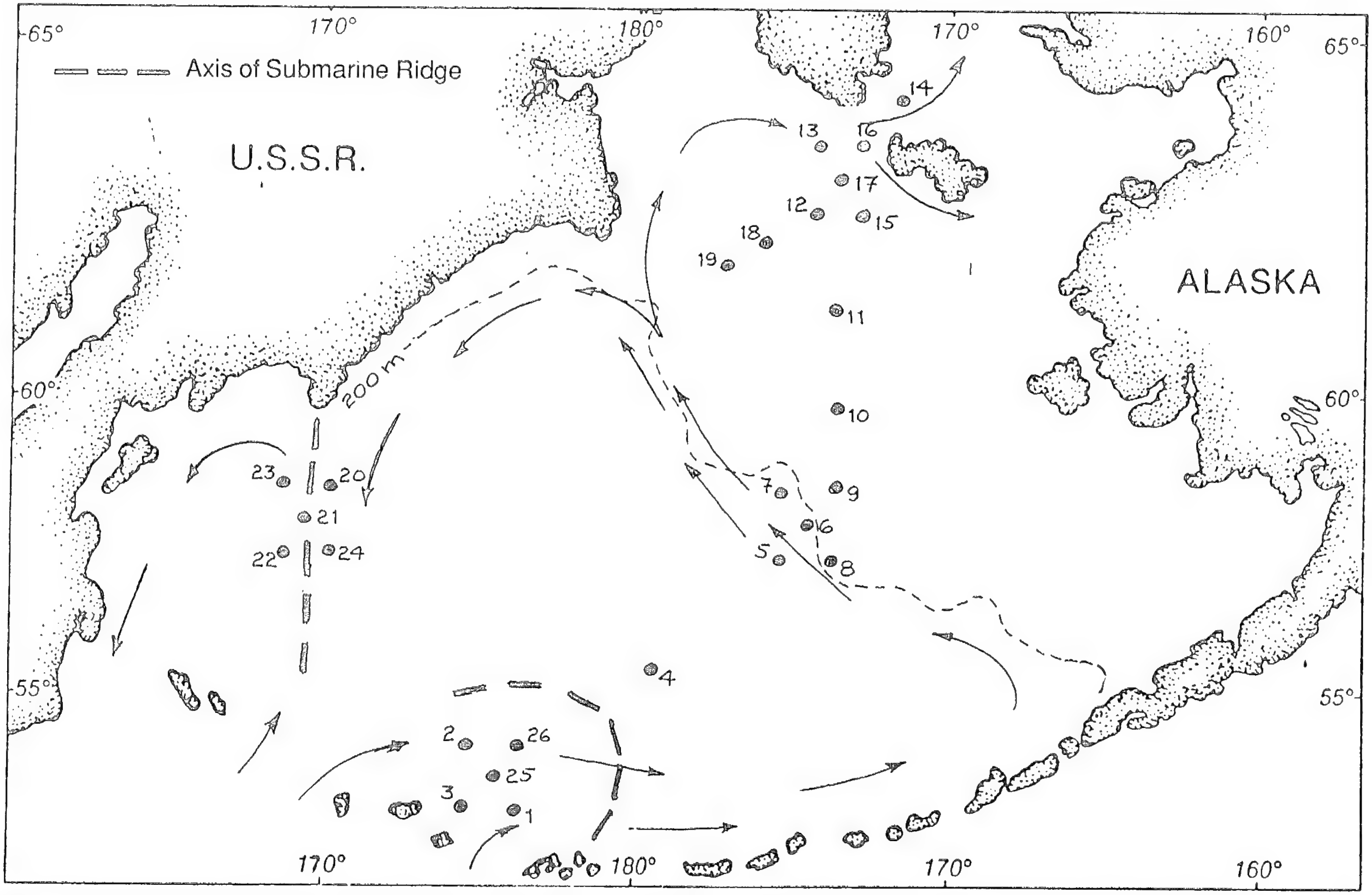

Fig. 1. Station locations of the Second Joint U.S./U.S.S.R. Expedition to the Bering Sea, 1984. The 200 m depth contour (location approx.) demarks the edge of the enormous eastern continental shelf; to the east and north is shelf and to the west and south, 3,000-m basins. The arrows suggest pertinent parts of the general circulation (cf. Hughes et al. 1974). Heavy dashed lines show approximate locations of Shirshov Ridge (in the west) and Bowers Ridge (in the south).

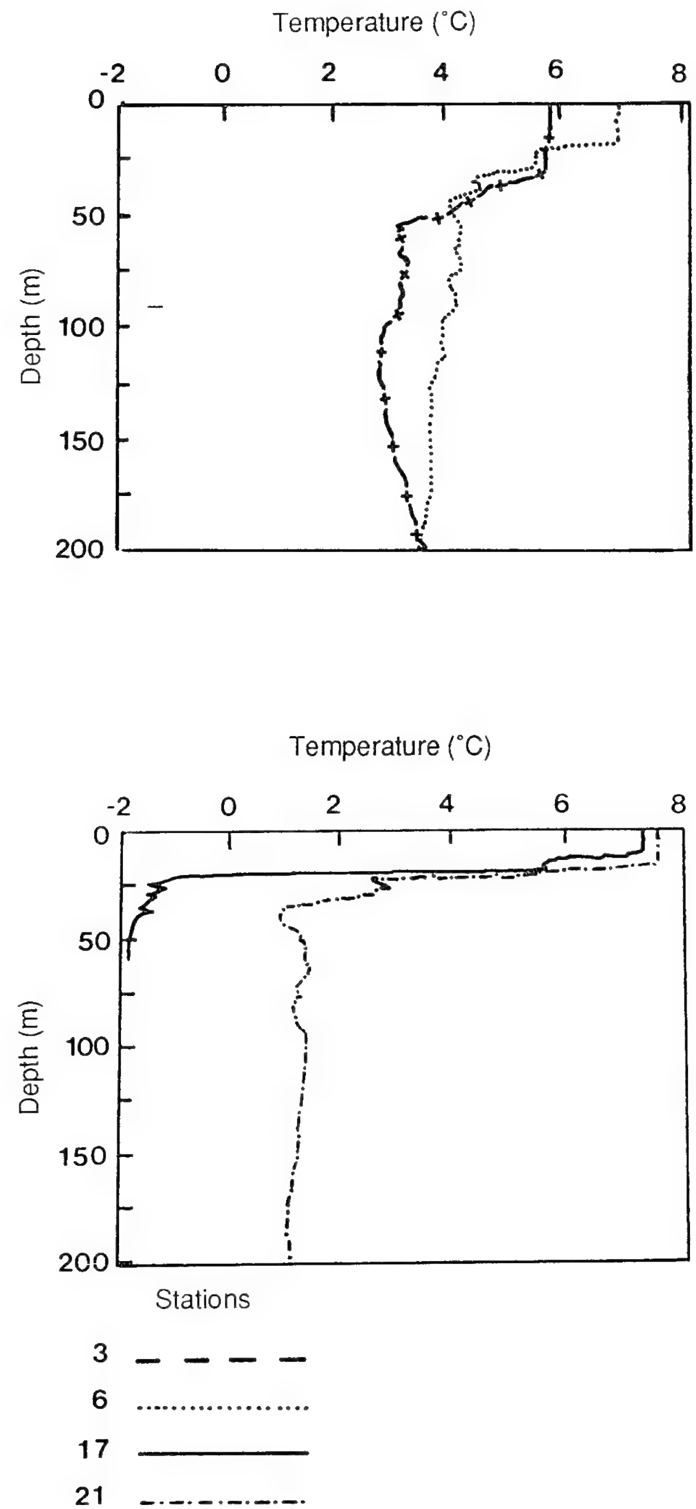

Fig. 2. Vertical temperature curves for 0-200 m at the center stations of the four polygons, from XBT data.

layers. With a smaller vertical density gradient, more heat can be transferred downward for the same insolation and turbulence, and surface temperatures are lower. The lower temperatures of the lower layer at stations influenced by shelf waters is an artifact of the previous winter's cooling; the deeper water of the continental shelves is insulated against strong heating over the summer by the lower salinity surface layer, and remains over summer the coldest water in the sea. On parts of the shelves, temperatures <0°C prevail throughout the year; see Coachman (1986), for a detailed discussion. Thus, the coldest waters were at the north polygon (station 17), in the bottom water of the central shelf. The next coldest were in the west polygon, located on the Shirshov Ridge (station 21), not so extremely cold as shelf-bottom water, but colder than the general open-basin waters at these depths. These temperatures reflect the particular conditions of the Karaginski Basin, which exhibits the coldest subsurface layers of the open Bering Sea away from the shelves (Sayles et al. 1979).

Currents

Circulation over the basins of the Bering Sea is in the most general sense cyclonic; this is suggested by the arrows in Fig. 1 (cf. circulation schemes in Hughes et al. 1974). But the deep basin is subdivided into three basins by the Shirshov Ridge, directed south from Cape Olyutorskiy and the arcuate Bowers Ridge in the south-central region. These topographic features strongly steer the flow field, as does the continental slope of the eastern shelf. In general, the flows tend to parallel isobaths, flowing along these features and not across them.

The circulation of the Bering Sea is not well known, but we do feel relatively certain about some features. The current flows eastward north of the Aleutian Islands, but apparently not as a well-defined ocean stream all of the time. The Bering Slope Current flows northwestward along the continental slope of the eastern shelf; its transport is of the order of 5 sverdrups (1Sv = 10^6 m^3/s). The flow appears to be southwest and south along the Koryak Coast and Shirshov Ridge. The Kamchatka Current flows south out of the sea along Siberia. Inflow is through Near Strait, probably quite steadily through its eastern portion, and on the average into the Bering Sea through most of the Aleutian Island passes (Favorite 1974).

On the eastern Continental Shelf proper, the major current is a branch of the Bering Slope Current, flowing northward around the periphery of the Gulf of Anadyr, thence through Anadyr Strait, and northward across the Chirikov Basin, exiting through Bering Strait. This current transports between 0.5 and 1Sv, varying significantly on time scales of a few days. Under certain circumstances, this flow bifurcates at Anadyr Strait; some of the water flows eastward south of St. Lawrence Island, but this is not the regular flow pattern and the amounts of water involved are not large.

Water Masses

We now discuss in more detail the water masses of each polygon, based on the observed upper-layer thermal structure. In some polygons there are considerable differences in temperature and vertical thermal structure between stations; these differences can all be traced to the location of the stations in relation to the currents. In these cases the stations of the polygons were not all located within the same water mass; rather they straddled oceanographic boundaries. This fact must be taken into consideration in interpreting any of the polygon results. Figure 2 shows vertical temperature curves for the center stations of the four polygons. Figures 3-6 show vertical temperature curves for the other stations at the four polygons.

South Polygon

Three notable differences are present among the five southern polygon stations, namely: (1)

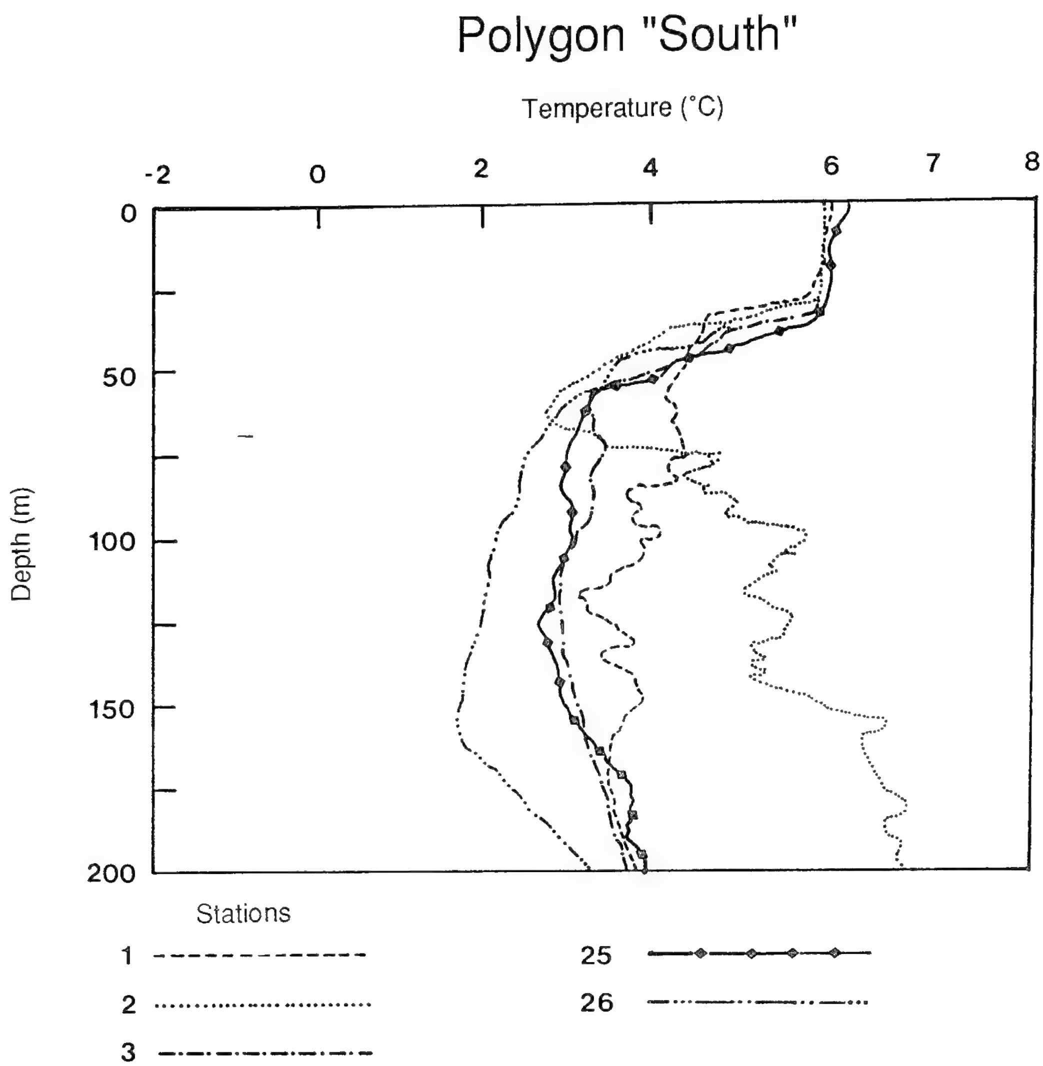

Fig. 3. Vertical temperature curves for 0-200 m for the five stations of the south polygon.

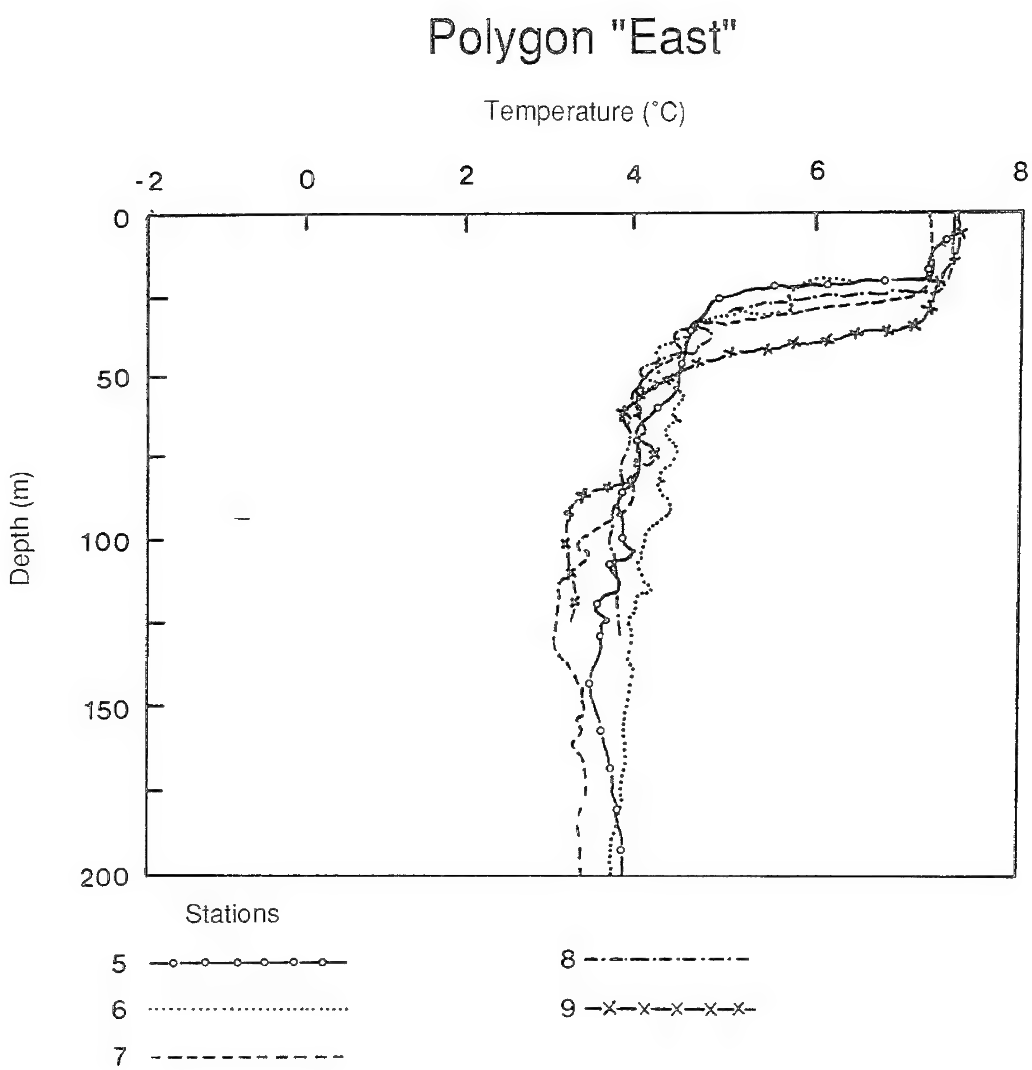

Fig. 4. Vertical temperature curves for 0-200 m for the five stations of the east polygon.

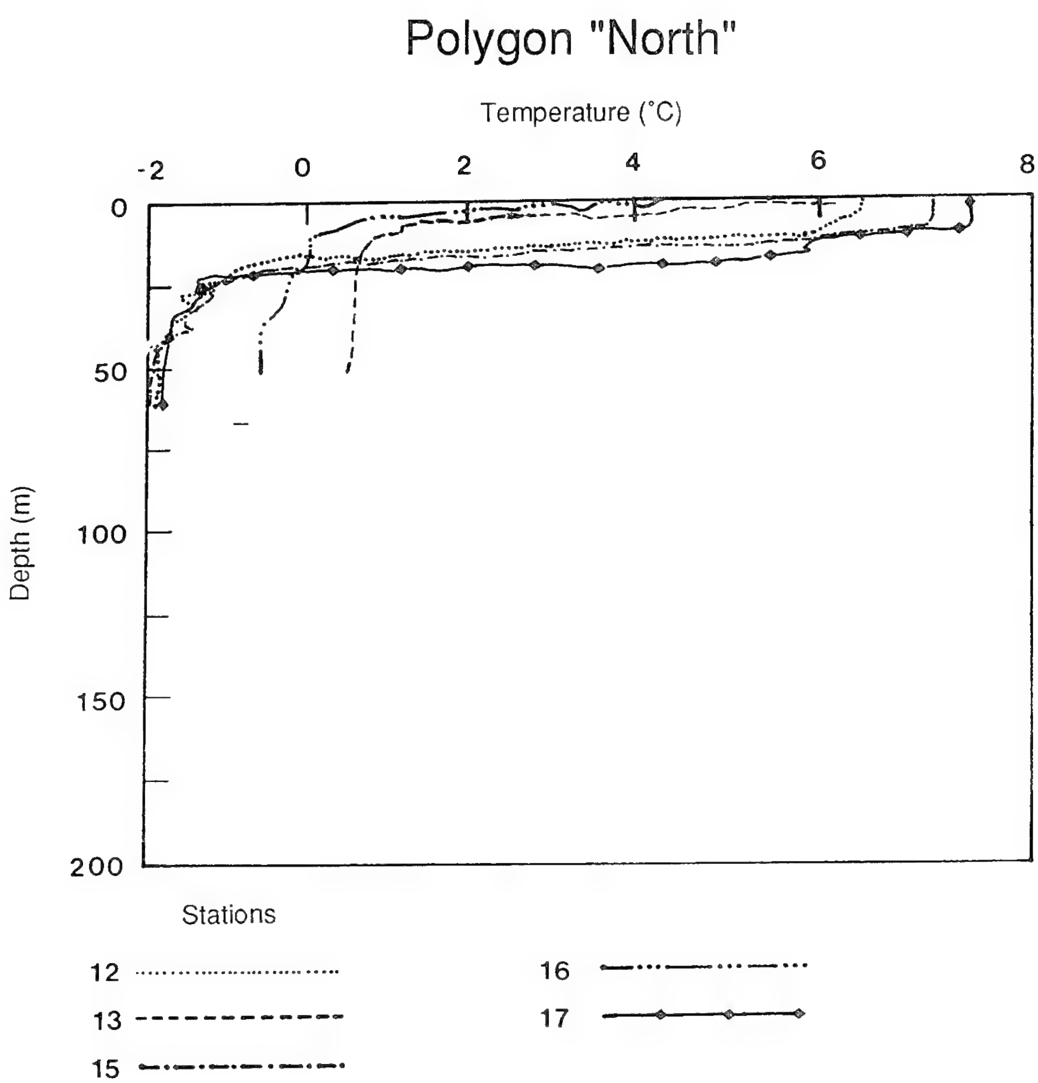

Fig. 5. Vertical temperature curves for 0-200 m for the five stations of the north polygon.

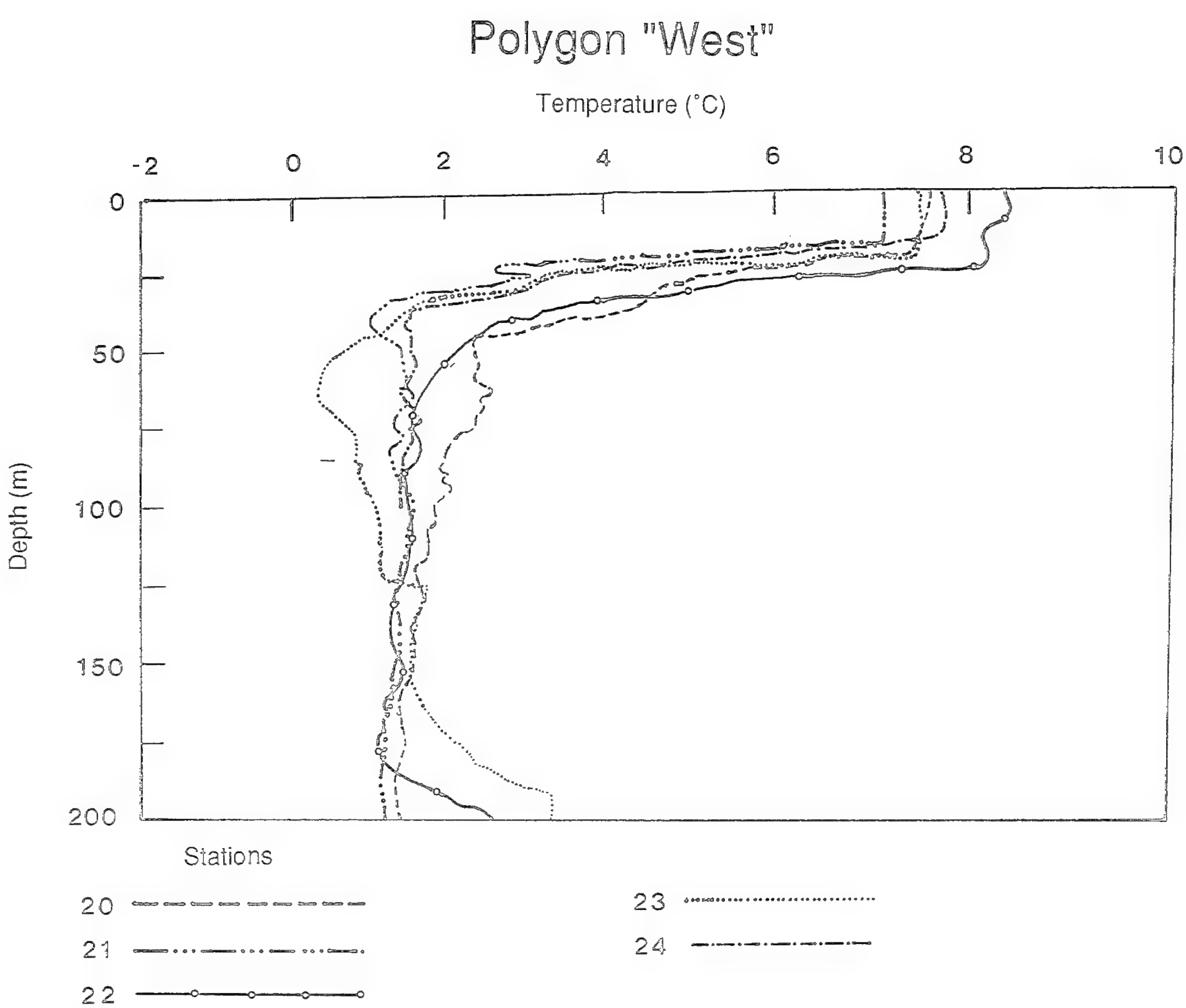

Fig. 6. Vertical temperature curves for 0-200 m for the five stations of the west polygon.

stations 25 and 26 showed much higher upper-layer temperatures than 1, 2, and 3; (2) stations 1 and 2 show strong evidence of vigorous lateral mixing (interleaving and layering) from 50 to 200 m compared with the others, which vary more smoothly, with colder water and a temperature minimum at about 125 m; (3) station 25 exhibits a much stronger temperature minimum at 150 m than the others. (See Fig. 3.)

The warmer surface layers at stations 25 and 26 can be ascribed directly to insolation over the approximately 22-day interval between occupations. The mean temperature above 40 m rose from 5.8°C to 7.4°C, a heating rate of 0.2 langley/min. London's data (Neumann and Pierson 1966) show insolation for this latitude and time of year to be 0.26 langley/min., excellent agreement considering that some of the heat was undoubtedly stirred down out of the surface layer.

The south polygon is located where there can be direct inflow from the North Pacific. Two major sources provide water to this location: Near Strait and Buldir Pass. Undoubtedly, streams from both sources, which are not providing water of precisely the same characteristics, are observed. The scale size of the streams (width) is less than the station spacing, and where different streams of inflow are juxtaposed, lateral mixing takes place (stations 1 and 2).

The strong temperature minimum at station 26 (northeast corner) is water of the central basin (to the north) or possibly even water from Karaginskiy; it is not water directly from the North Pacific (at least at these depths).

To summarize (cf. station locations in Fig. 1): stations 3 and 25 are within inflow from the North Pacific, which does not extend north to station 26; stations 1 and 2 show strong lateral mixing.

East Polygon

The east polygon is located over the continental slope of the eastern shelf; two stations (8 and 9) were actually on the outer shelf. Its water conditions are the most homogeneous of any of the polygons. The upper-layer water (25-40 m) is typical of the outer shelf regime at this time of year. It overlies the so-called Alaska Stream/Bering water mass (Coachman and Charnell 1979), which has temperatures all year round of 3.8°C to 4.0°C and is the primary source of water to the outer Continental Shelf regime (Coachman 1986). (See Fig. 4.)

The east polygon is not in a location (at least at the time of observations) where water at midshelf depths (about 100 m) is flowing out from the shelf. If this were happening, there would be a strong temperature minimum signal at these depths (cf. Kinder et al. 1975).

North Polygon

Two very different water masses were sampled at the five northern polygon stations: Central shelf water (stations 12, 15, and 17), and Anadyr Current water (stations 13 and 16). (See Fig. 5.)

Central shelf water attains very low temperatures to the bottom because of cooling and ice formation during winter. Over spring and summer, following establishment of a less dense surface layer (first through lowered salinities from ice melt and then trapping of insolation in the surface layer), the bottom water is isolated, warmed only by extremely slow vertical diffusion. The coldest water in the whole Bering Sea in summer is that of the central shelf bottom, and the very coldest is that of the northwest part of the central shelf, southwest from St. Lawrence Island (the so-called "cold center" of the Bering Sea; Barnes and Thompson 1938). The middle and two south polygon stations of the north polygon sampled this water, which, even in July, was apparently barely above freezing (Note: the XBT's are not accurate, and we do not have salinities).

The Anadyr Current is a northward branch from the Bering Slope Current, in response to

the demand for across-shelf flow created by the northward transport through Bering Strait. The current is concentrated toward the west end of the shelf as a western boundary current (Kinder et al. 1986). This flow hugs the periphery of the Gulf of Anadyr, following the bathymetry and circulating around the "cold center" water of the central shelf regime (see above). It carries nutrient-rich water from the Bering Slope Current, which has temperatures of 3.5°C to 4°C. There is some lateral mixing in transit with the "cold center" water, the waters along the eastern side of the current closest to central shelf water being cooled the most through the mixing (Coachman et al. 1975). Thus, station 13 represents the "purest" Anadyr Current water, while station 16 shows the effect of some cooling from the lateral mixing.

There is also effective vertical mixing in the Anadyr Current, which is why the water columns are mixed almost to the surface. There is only the thinnest of surface layers present at this time, due to small admixtures of coastal water from Siberia (Anadyr River). The weather conditions were calm; a thin surface layer would be mixed away in moderate winds.

To summarize: pure Anadyr Current water was observed at station 13, the main part of the current passing to the west and north of station 16. The polygon center (station 17) and south two stations (12, 15) were in central shelf water.

West Polygon

The polygon is located over the crest of the long submarine ridge (Shirshov Ridge) that extends south from Cape Olyutorskiy. Stations 20 (in the northeast) and 23 (in the northwest) differ from each other and from the other three. Station 20 shows relatively warm (about 2°C) water at 75 m and no temperature minimum, while station 23 shows a strong minimum of 0°C at the same depths. The other three stations, located farther south, show values intermediate between these in the subsurface layer. (See Fig. 6.)

The flows near submarine ridges are strongly guided by the bathymetry and sometimes even flow in opposite directions near the Shirshov Ridge (Hughes et al. 1974). We interpret that stations 20 and 23 are samples of different water masses, while the others represent blendings of the two. We deduce that station 20 in the northeast is water from the extension of the Bering Slope Current that has come southwest and is now flowing south along the ridge. The thermal structure is characteristic of Bering Slope Current water, and is only slightly cooled from what was observed in the east polygon. Station 23, on the other hand, shows the relatively strong (0°C) temperature minimum in subsurface layers typically associated with water of the Karaginskiy Basin. We surmise this water is related with waters to the west. The flow direction might also be to the south, because those stations (21, 22, 24) could represent mixtures of the two water masses, but without other evidence, this is conjecture.

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Chemical Oceanography

DISTRIBUTIONS OF OXYGEN AND DISSOLVED INORGANIC NITROGEN IN RELATION TO THE BIOLOGICAL PRODUCTIVITY OF THE BERING SEA

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Introduction

Several concepts relate net chemical changes to biological production in surface ocean waters. For example, new production is a subset of total phytoplankton production and is defined by the uptake of nitrate and ammonium (Dugdale and Goering 1967). Although cyanobacteria are ubiquitous in surface waters, the overall rates of nitrogen fixation measured thus far are relatively low (Capone and Carpenter 1982). Thus, nitrate production is thought to be the dominant factor in new production (Eppley 1988). The proportion of new to total nitrogen production (f) is an index of the relative amount of total production available for export (Eppley and Peterson 1979). Net community production is defined as gross phytoplankton photosynthesis minus phytoplankton and heterotrophic respiration and can be estimated from oxygen or total dissolved inorganic carbon changes (Codispoti et al. 1986; Minas et al. 1986).

The similarity between the elemental composition of ocean plankton and the oxidative ratios of carbon, nitrogen, and phosphorus has been well established (Redfield et al. 1963). Based on the assumption that these stoichiometric ratios describe the kinetic relationships among ocean elemental cycles, element-specific production estimates can be related through the stoichiometry of the Redfield equation (Redfield et al. 1963):

$$106\ CO_2 + 16\ NO_3 + PO_4 = C_{106}N_{16}P + 132\ O_2 \qquad (1)$$

For example, several workers in the United States have used new (nitrate) production to estimate net community production (NCP) on the basis of Redfield stoichiometry (Eppley et al. 1983; Codispoti et al. 1986). Also, net community production estimates have been based on a mass balance of chemical change in the water column (Schulenberger and Reid

1981; Jenkins 1982). This paper presents new data from the Bering Sea that can be used for chemical mass-balance estimates of biological production.

The Bering Sea is not well sampled in terms of biological rate processes. Like most of the subarctic North Pacific, the oceanic areas of the Bering Sea exhibit the enigmatic combination of large surface nutrient concentrations coupled with low standing crops of phytoplankton (Whitledge et al., this report). However, this contrasts sharply with the shelf areas; on both the huge eastern shelf and in the Bering Strait, chemical and biological measurements indicate that productivity rates are among the highest in the world ocean (Sambrotto et al. 1984, 1986). The sampling done during the 1984 joint U.S.-U.S.S.R. expedition afforded a rare opportunity to analyze both oceanic and shelf areas.

Methods

Chlorophyll *a*, nitrate, nitrite, ammonium, silicate, and phosphate were routinely determined onboard on samples from discrete depths. Discrete chlorophyll *a* measurements were made using the acetone-extracted fluorescence method (Parsons et al. 1984). Nutrient analyses were made by standard automated techniques (Whitledge et al. 1981). Particulate carbon (PC) was measured less frequently than the above constituents, but allowed for the determination of regional and temporal changes. Samples for particulate carbon were collected onto precombusted glass-fiber filters (Whatman type GF/F), and analyzed on a Perkin-Elmer model 240C CHN analyzer.

Results

The oxygen and nitrogen distributions along the major track of the expedition are presented elsewhere in this report. These data clearly indicate the observed transition between the low-new-production oceanic areas and the elevated new production taking place on the eastern shelf. A more detailed view of the distribution of oxygen in shelf waters is presented in Fig. 1. This figure expands on the shelf data presented in the longer section. Layers of intense new production are indicated by the large net oxygen accumulations at depth. Apparently, the flow of water north through Anadyr Strait keeps the water column mixed vigorously and prevents the formation of a distinct subsurface layer of oxygen (e.g., stations 16 and 14). However, at stations out of the pass (and therefore out of the main flow) much greater concentrations accumulate (e.g., stations 19 and 15).

The distribution of plant biomass as measured by chlorophyll did not exhibit a clear correlation with nutrient fields. No clear relationship was found between chlorophyll *a* and phosphate (Fig. 2) and the situation changes only slightly in the case of ammonium (Fig. 3), nitrate (Fig. 4), and silicate (Fig. 5). In each of these latter cases, there is a tendency for the larger chlorophyll values to be associated with lower nutrient concentrations. However, most chlorophyll values appear to be independent of ambient nutrient concentrations.

The relationships among the nutrient concentrations themselves are more obvious. Phosphate and nitrate are strongly correlated throughout the study area (Fig. 6). The same is true of silicate and nitrate, although in deep, nutrient-rich waters, their relationship is markedly different from that in surface waters (Fig. 7). Only in the case of ammonium and nitrite, two intermediates in the nitrogen cycle, is the correlation between them weak (Fig. 8).

Discussion

Chemical parameters such as oxygen and nutrient distributions reflect the biological and physical dynamics of the region and therefore are powerful but very complex variables to interpret. The physics of this region is covered in a general sense elsewhere in this volume

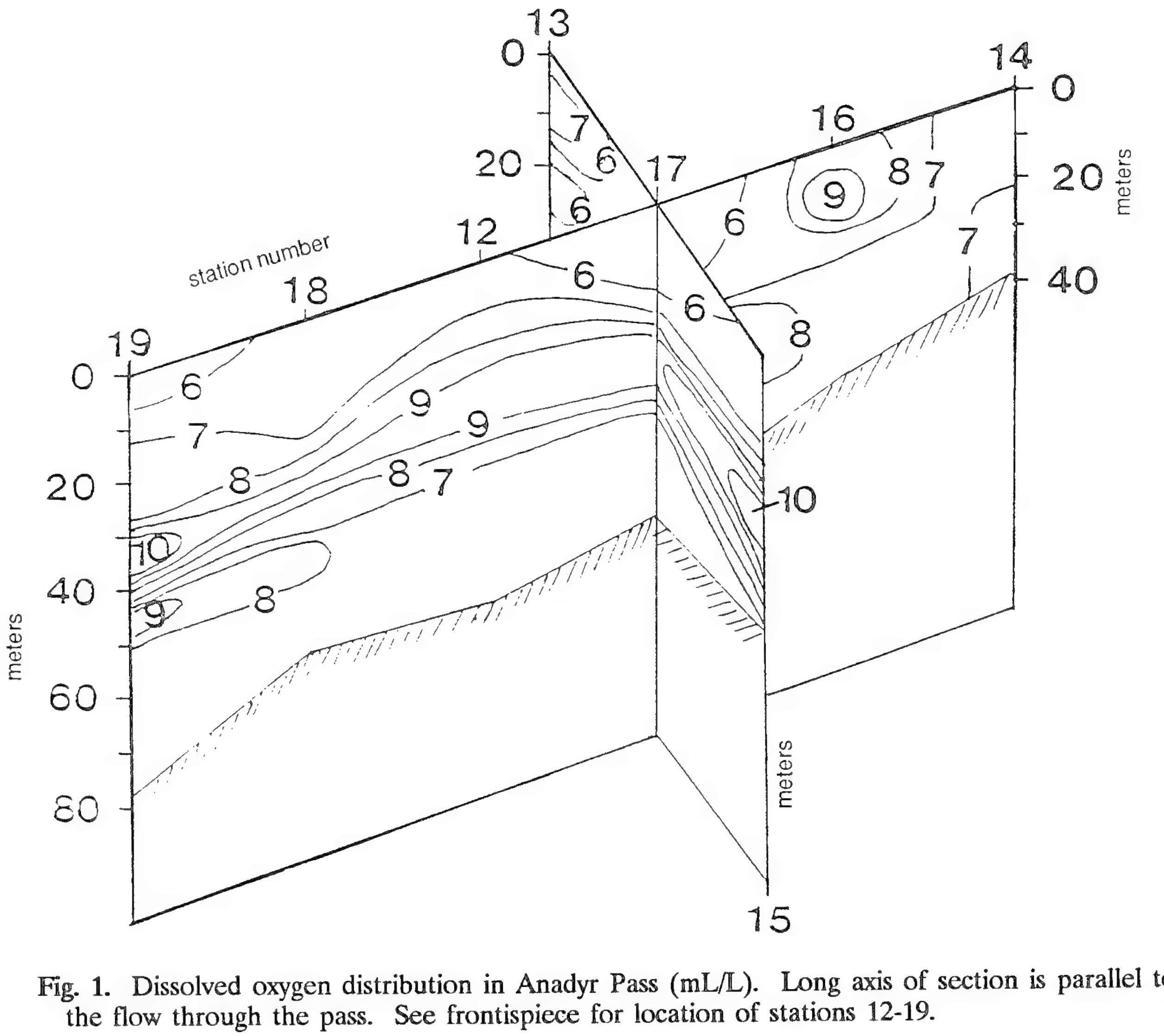


Fig. 1. Dissolved oxygen distribution in Anadyr Pass (mL/L). Long axis of section is parallel to the flow through the pass. See frontispiece for location of stations 12-19.

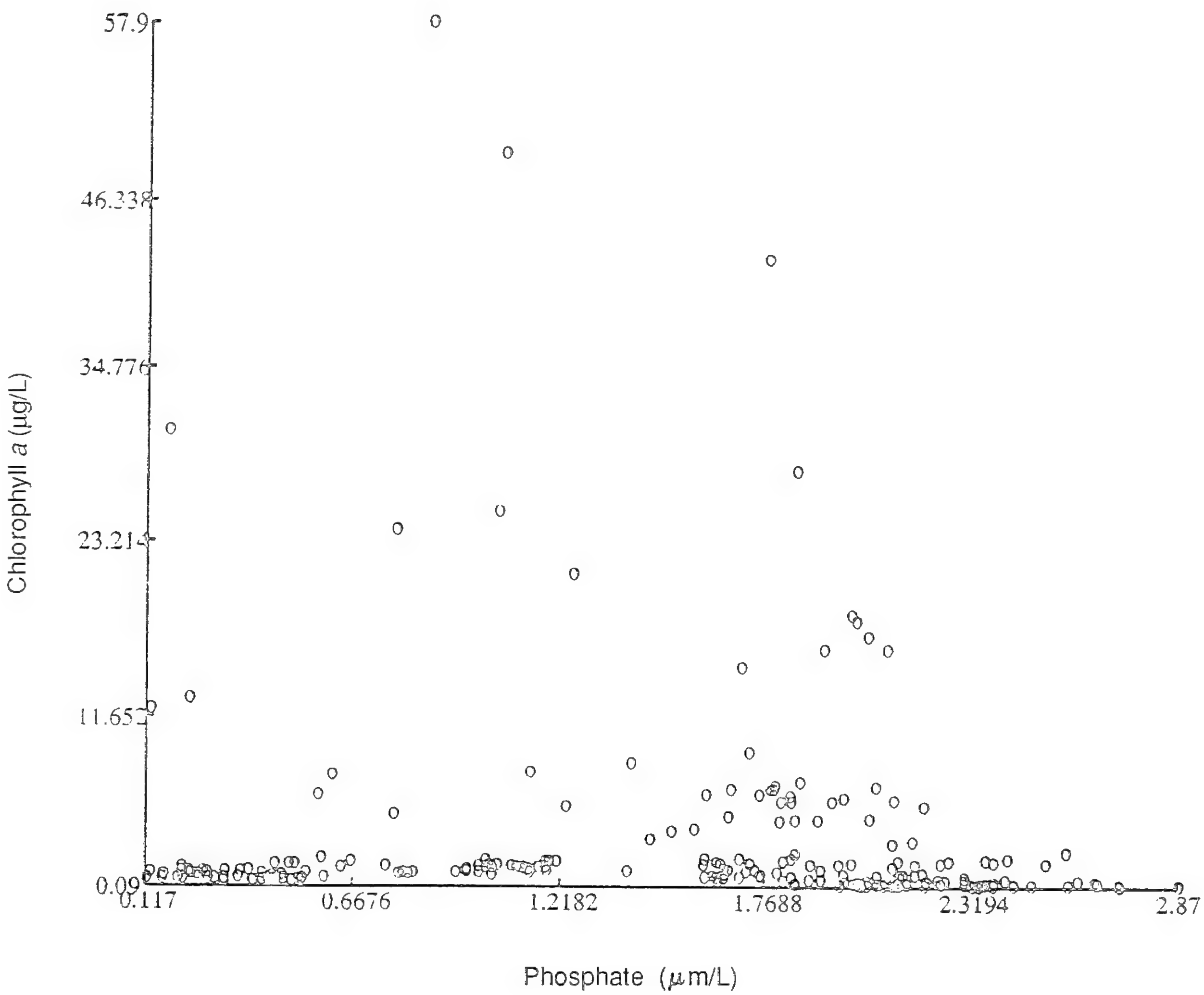


Fig. 2. Extracted chlorophyll *a* vs. phosphate concentration.

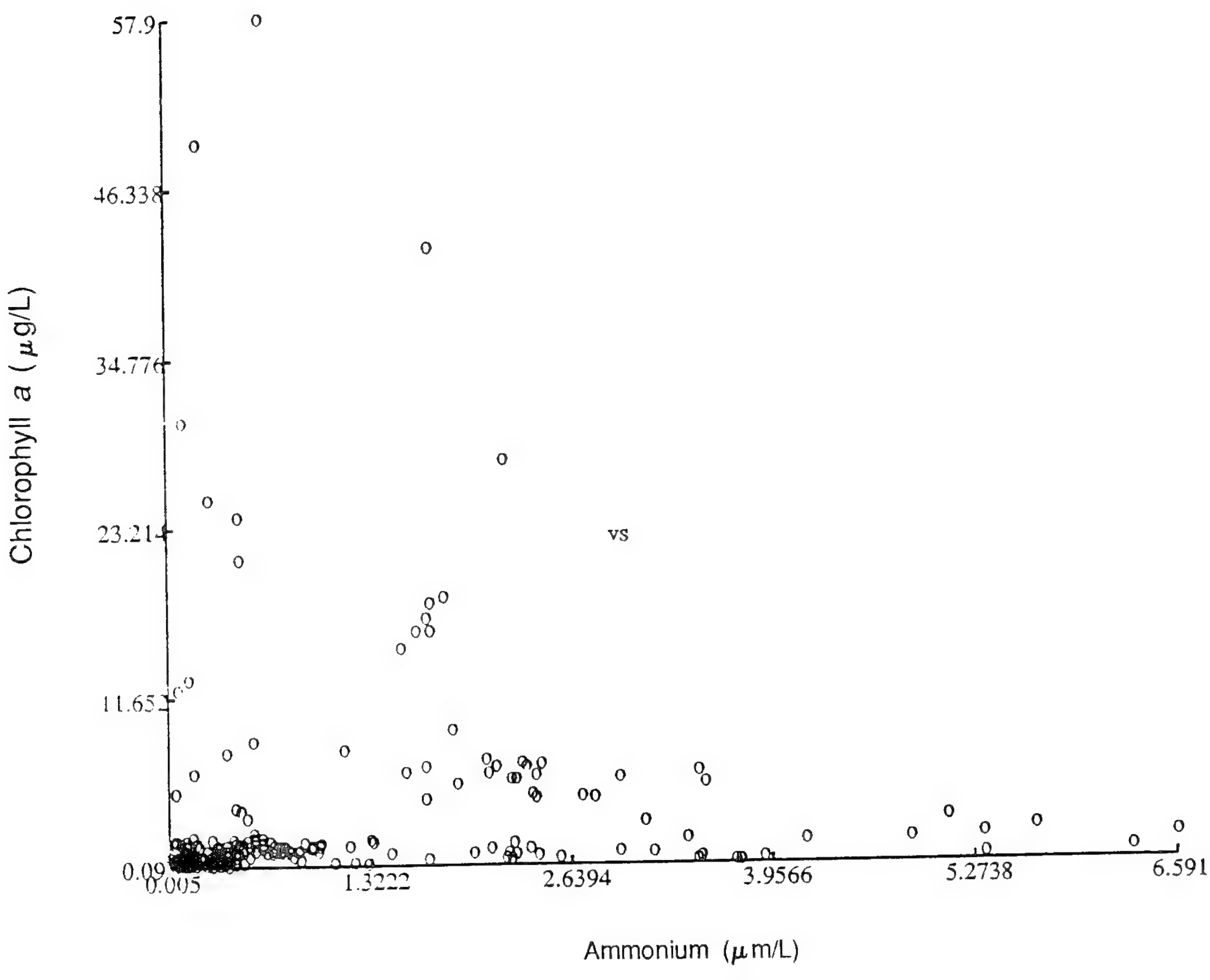


Fig. 3. Extracted chlorophyll *a* vs. ammonium concentration.

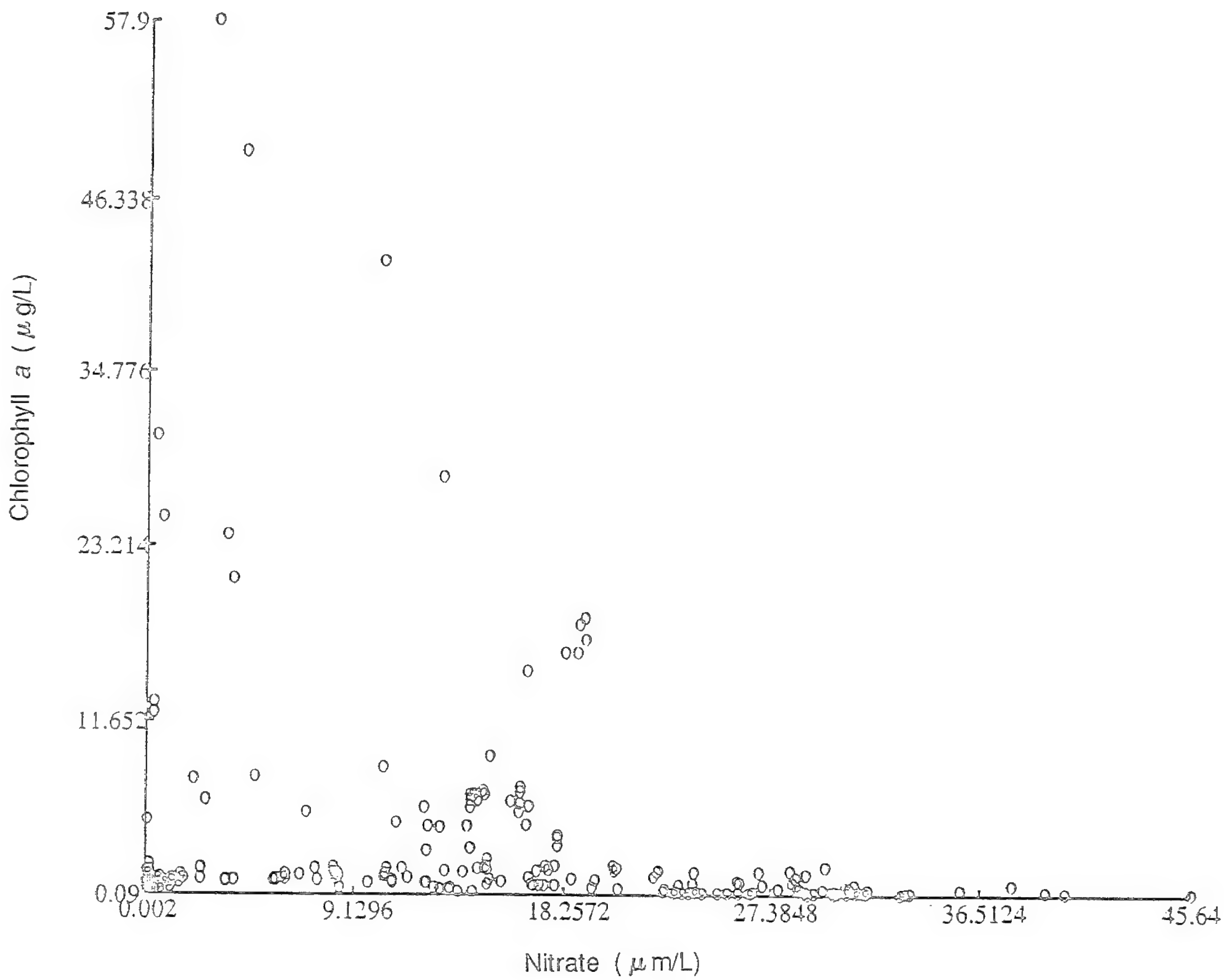


Fig. 4. Extracted chlorophyll *a* vs. nitrate concentration.

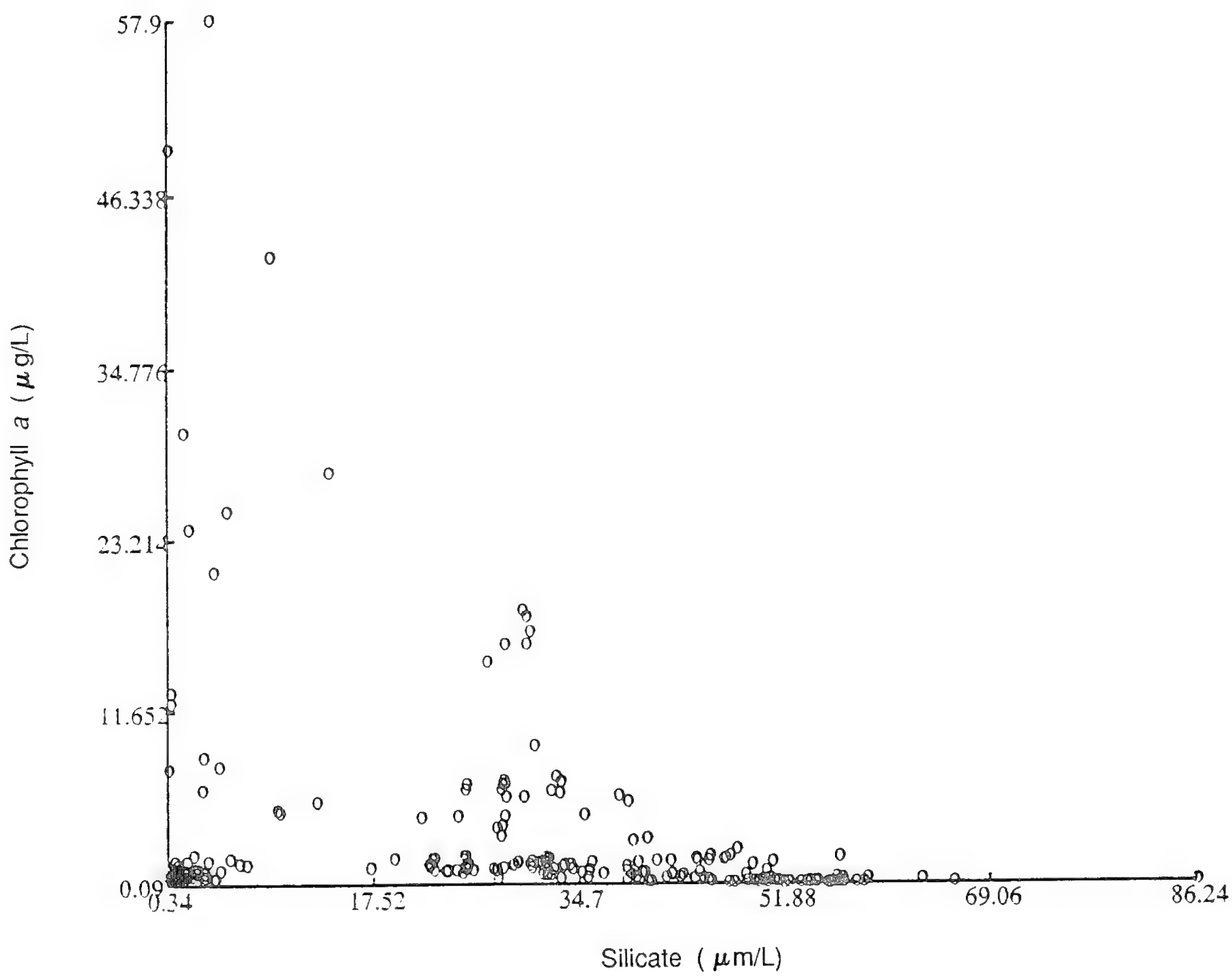


Fig. 5. Extracted chlorophyll *a* vs. silicate concentration.

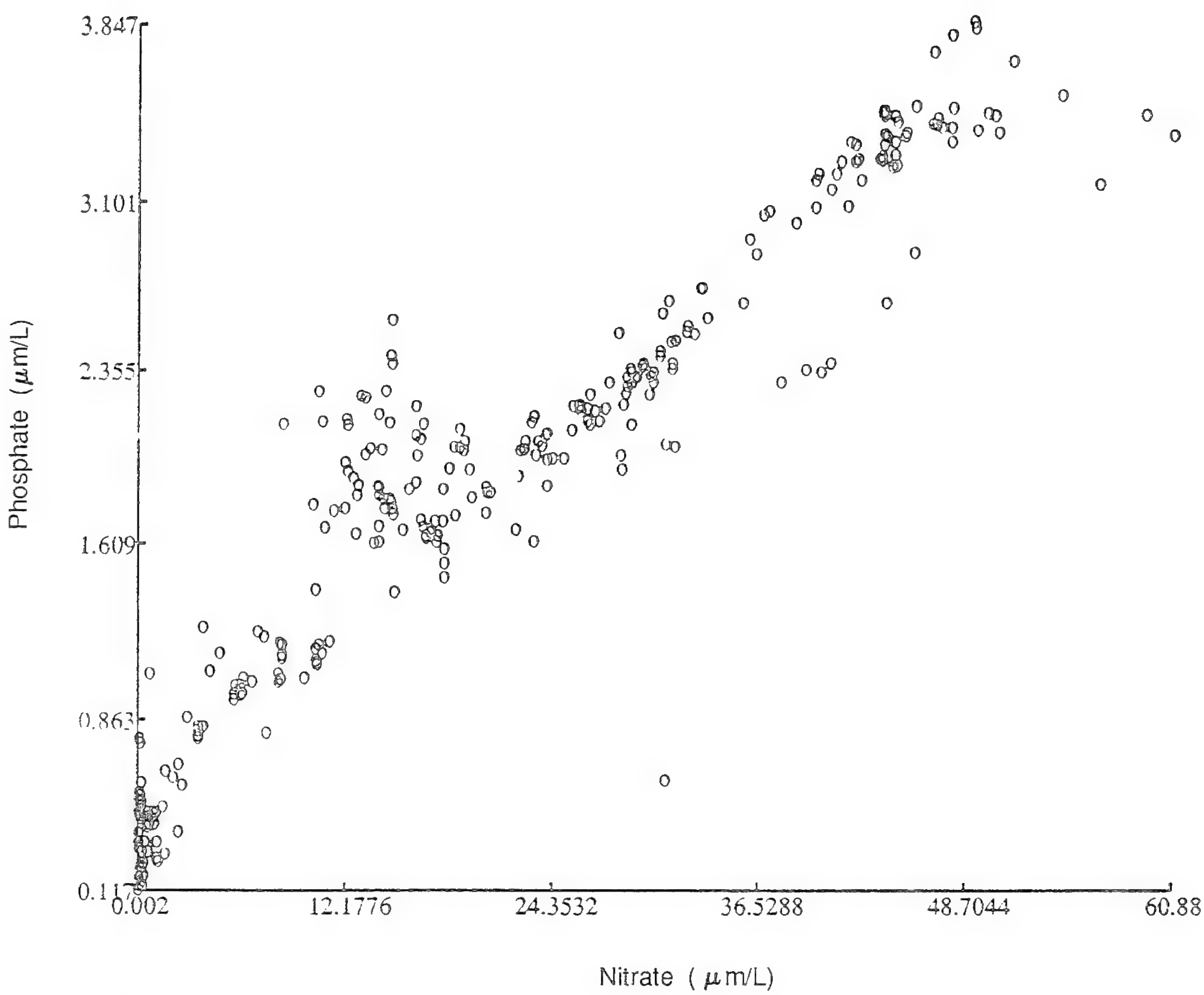


Fig. 6. Phosphate vs. nitrate concentration.

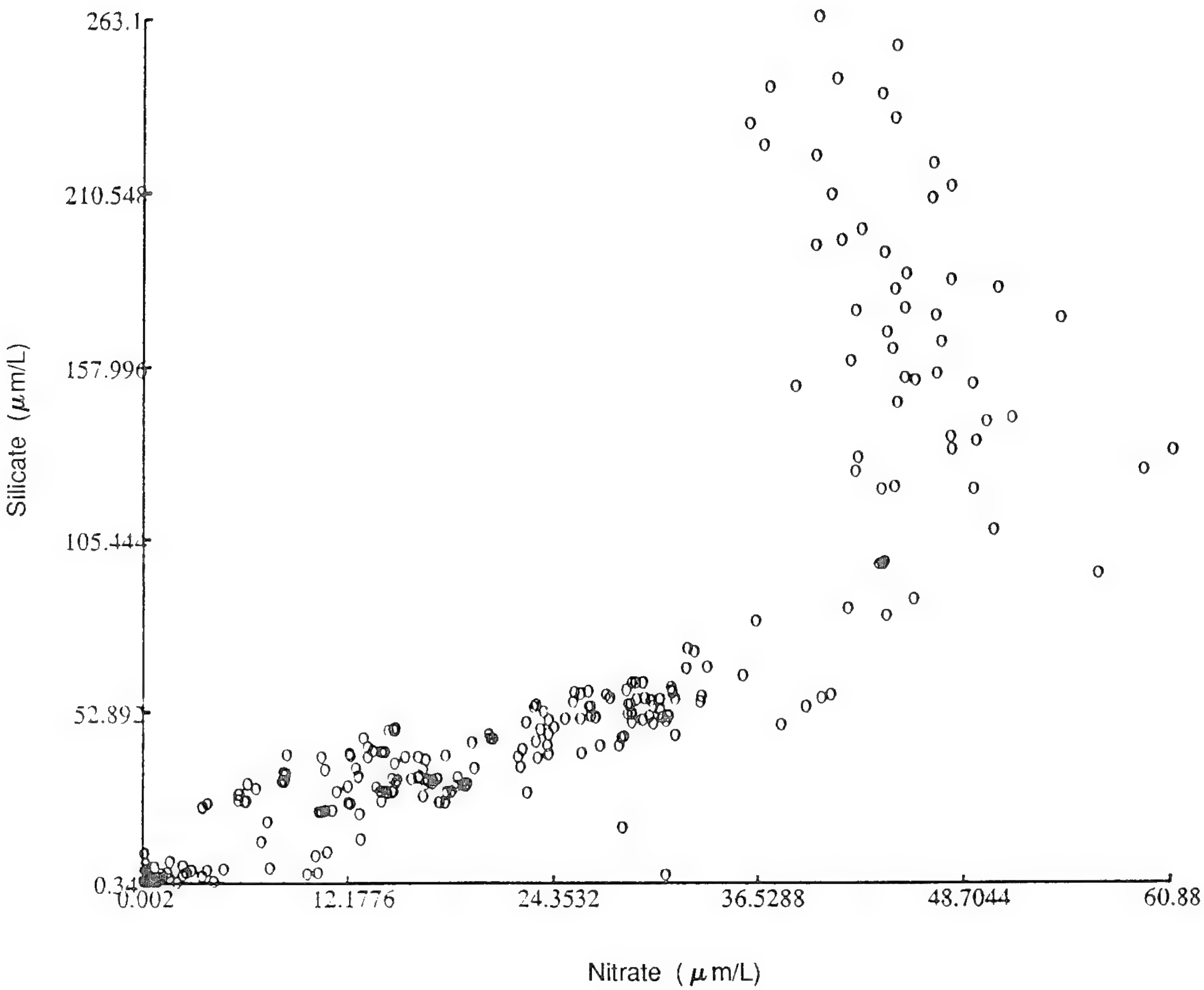


Fig. 7. Silicate vs. nitrate concentration.

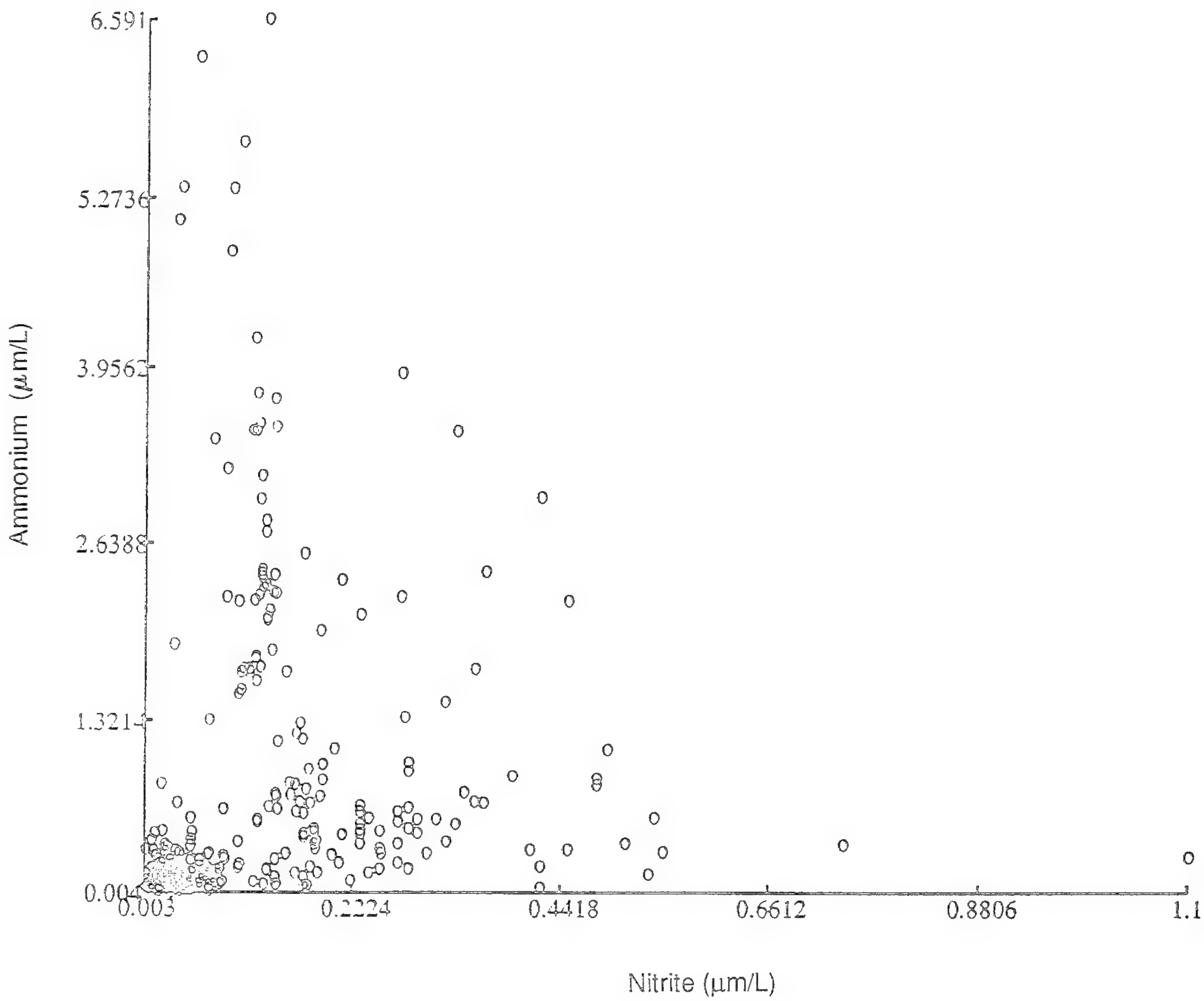


Fig. 8. Ammonium vs. nitrite concentration.

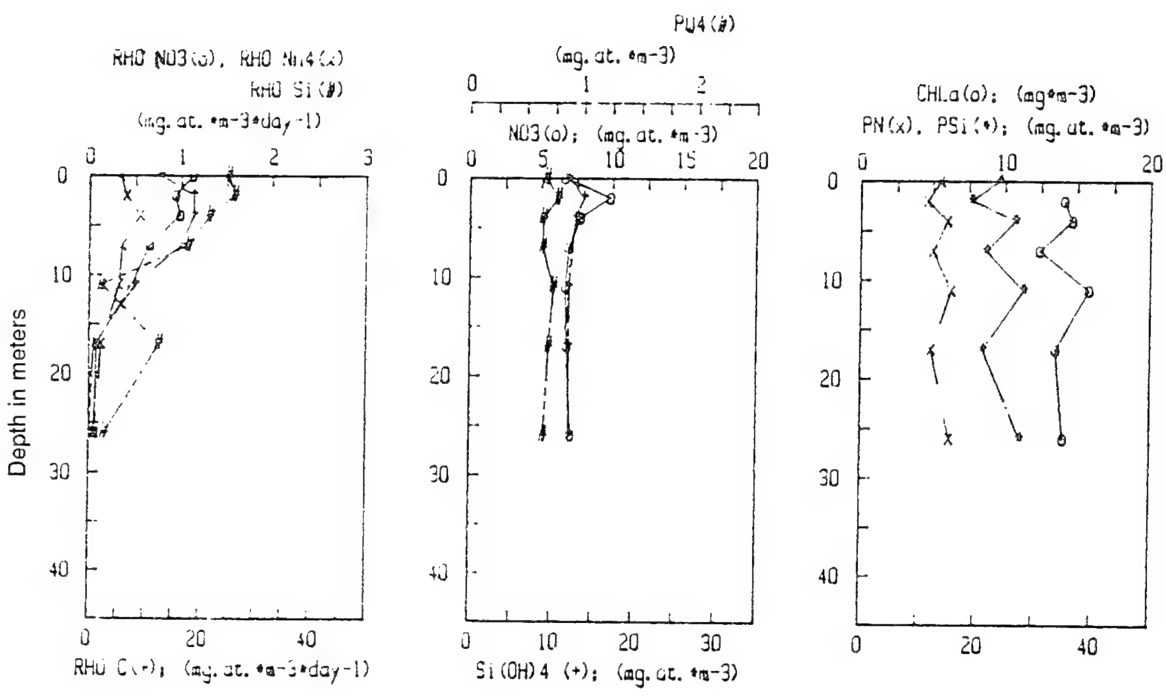
(see Coachman). The present discussion pertains mainly to the biological processes involved in creating the observed patterns. For example, the ratio of particulate carbon to chlorophyll (wt.:wt.) was significantly greater in shelf areas (about 60) than in oceanic areas (about 30). This difference is probably due to biological differences such as photoadaptation and grazing. Also, from previous sampling of biological rates in the Bering Sea, it is clear that the shelf areas are much more productive than the oceanic areas.

To illustrate this point, consider the contrast between the elevated productivity measured during spring on the shelf (Fig. 9) with the much lower production in deeper water in the southeastern Bering Sea (Fig. 10). The differences between the nitrate productivity in Figs. 9 and 10, if applied to Bering Sea shelf and oceanic areas generally, account for the marked difference in annual nitrate cycles observed in the two areas. In the shelf areas, a pronounced spring bloom depletes surface-water nitrate across most of the eastern shelf. In contrast, the lower nitrate uptake rates in the oceanic areas account for the fact that surface-water nitrate is never depleted in these areas. There is no generally accepted explanation for the difference in new production between the shelf and oceanic areas at this time.

However, there are two leading hypotheses, one biological and the other chemical in nature. The biological explanation holds that the intense rate of grazing by a combination of macrozooplankton and microzooplankton prevents a large buildup of biomass, and so prevents the oceanic area from being more productive. The chemical explanation holds that the lack of iron as a nutrient for phytoplankton limits productivity in these areas. Although these hypotheses were developed largely in response to work in the North Pacific, the data collected during the joint 1984 cruise indicate that the Bering Sea is an excellent laboratory in which to pursue these exciting research topics.

The relationship of chlorophyll to nitrate (Fig. 4) is very similar to the relationship found between chlorophyll and silicate (Fig. 5). This suggests that the organisms driving much of the productivity are diatoms, because diatoms require silica as well as nitrogen. This conclusion is also supported by the dominance of diatom pigments as biomarkers found throughout the study area during this expedition. The relationship between phosphate and nitrate (Fig. 6) also exhibits a chemical signature that may be of biological origin. Specifically, the presence of a nonzero intercept (phosphate remains at zero nitrate) suggests that denitrification may be an important process in the Bering Sea. The poor correlation of ammonium to chlorophyll distribution may be due to the role of temperature in controlling the turnover times of ammonium (Kanada et al. 1985).

The relationship among the cycles of biologically active substances in ocean waters is central to improved models of marine ecology. These relationships will be directly relevant to studies addressing the flux of man-made substances through marine ecosystems. Clearly, much more work needs to be done in these areas. In future joint work, more detailed rate measurements will be available. When these data are integrated into the developing detailed information on Bering Sea biology and chemistry, a much better understanding of the ecological response to human changes in the marine environment will be possible.



a) productivity b) nutrients c) standing crop

Fig. 9. Spring (29 April 1978) productivity, dissolved nutrients, and standing crop measurements at a representative Bering Sea shelf station, at 56°35'N, 164°58.2'W, and sonic depth of 91 m.

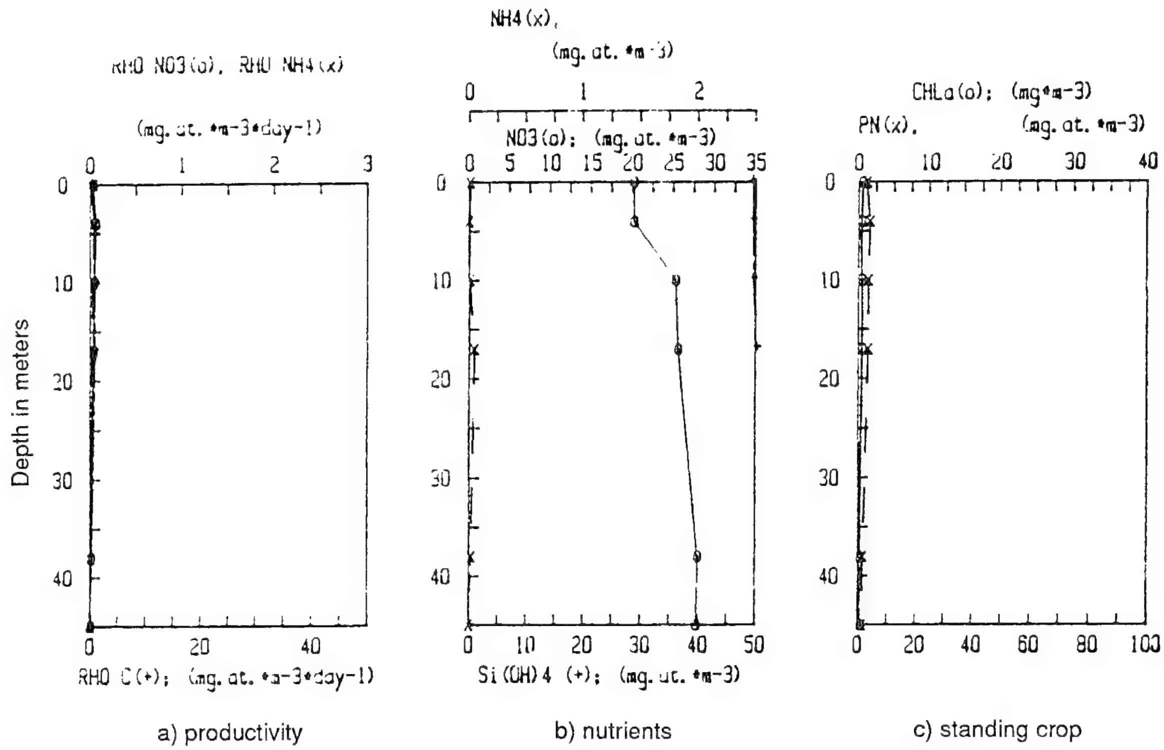


Fig. 10. Spring (23 April 1978) productivity, dissolved nutrients, and standing crop measurements at a representative Bering Sea shelf station, at 55°23'N, 168°57.8'W, and sonic depth 1,975 m.

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BIOAVAILABILITY AND REGENERATION OF NUTRIENTS

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Inorganic nutrients, along with carbonate, form the foundation for primary production processes that become the base for all life in the marine environment. The quantity of nutrients and the availability of light for photosynthetic processes varies throughout the oceanic regime with regard to both physical and biological processes that have been active. The joint U.S.-U.S.S.R. ecological study of the Bering Sea in 1984 offered an opportunity to investigate the relative quantity of nutrients available for primary production in four separate regions in the south, east, north, and west where polygons of stations were occupied (frontispiece).

Nitrogen

Nitrogen is the element most often limiting primary production in the ocean. The oxidized form of nitrogen (nitrate) is present in all parts of the sea except in special areas where the near-surface waters have been depleted by biological uptake. Physical mixing processes induced by wind, tides, or currents produce a vertical flux of nitrate in all areas of the ocean, but often the primary production processes will continually use and maintain low near-surface concentrations. In the following discussion the center station of each of the polygons will be used to represent the polygon regions, although in some instances, the polygons crossed water-mass boundaries, which reduces the validity of treating all of the stations of these polygons as replicates.

The south polygon contained more than twice as much nitrate (approximately 18 μg-at/L) in the upper mixed layer than the other polygons (Fig. 1). This surface water was very similar to typical North Pacific water; nutrient content and temperature conditions observed during this expedition support this interpretation. The surface waters in both the south and east polygons contained plentiful quantities of nitrate for primary production; however, the north and west polygons had much lower concentrations, which could inhibit phytoplankton growth. The vertical gradient of nitrate was very large on all stations, especially those locations with small surface values. These gradients are representative of strong vertical stratification (Fig. 2) combined with phytoplankton uptake that is depleting nitrate in the surface waters. The low nitrate uptake in the south polygon can be attributed to the presence of only a small phytoplankton population, which is continually grazed by zooplankton.

The smallest nitrate concentrations were observed in relatively low-salinity surface water (Fig. 3). At salinities above 32 ppt, nitrate displayed a relatively conservative behavior. The Bering Shelf water with typical salinities of 32 ppt - 33 ppt contained up to 30 μmole nitrate/L, but Anadyr water with salinities greater than 33 ppt had nitrate concentrations ranging from 20-40 μmole/L. This high-salinity water was formed the previous winter (Barnes and Thompson 1938) in the central shelf and Anadyr Gulf and also contributes to very high nitrate concentrations.

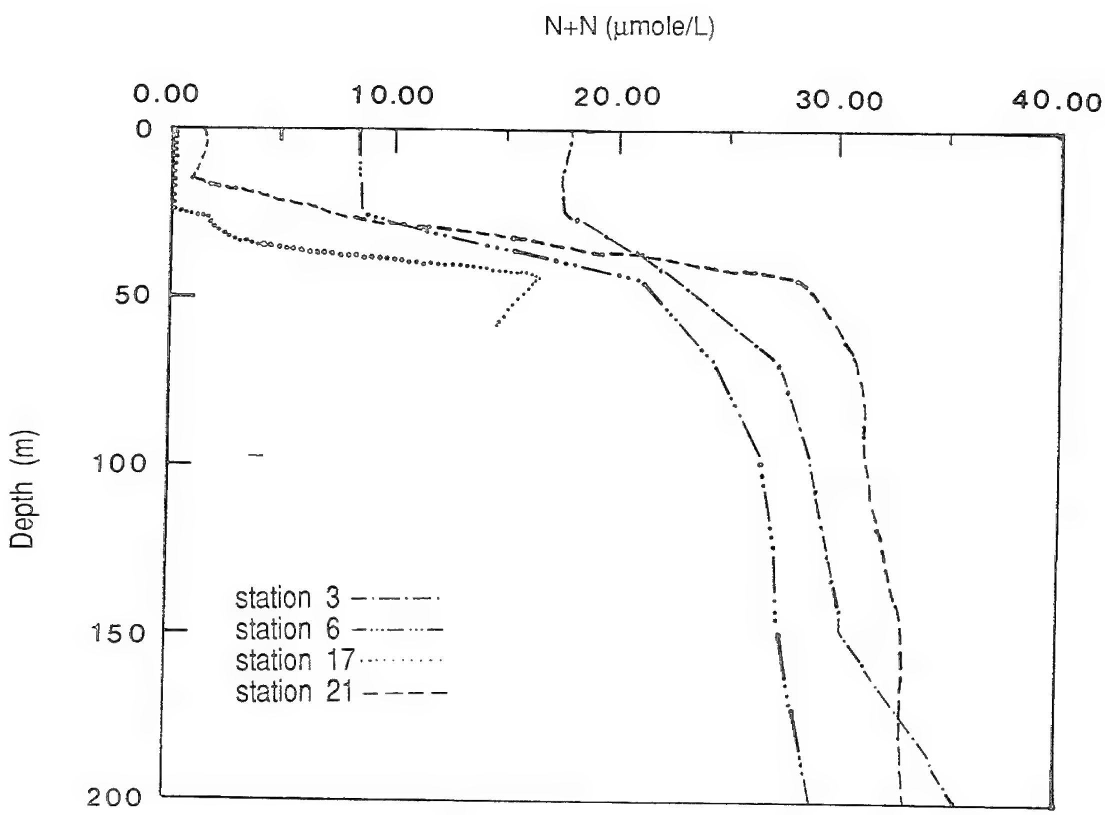

Fig. 1. Vertical distribution of nitrate plus nitrate concentration in the center of four polygons in the Bering Sea, 27 June-31 July 1984.

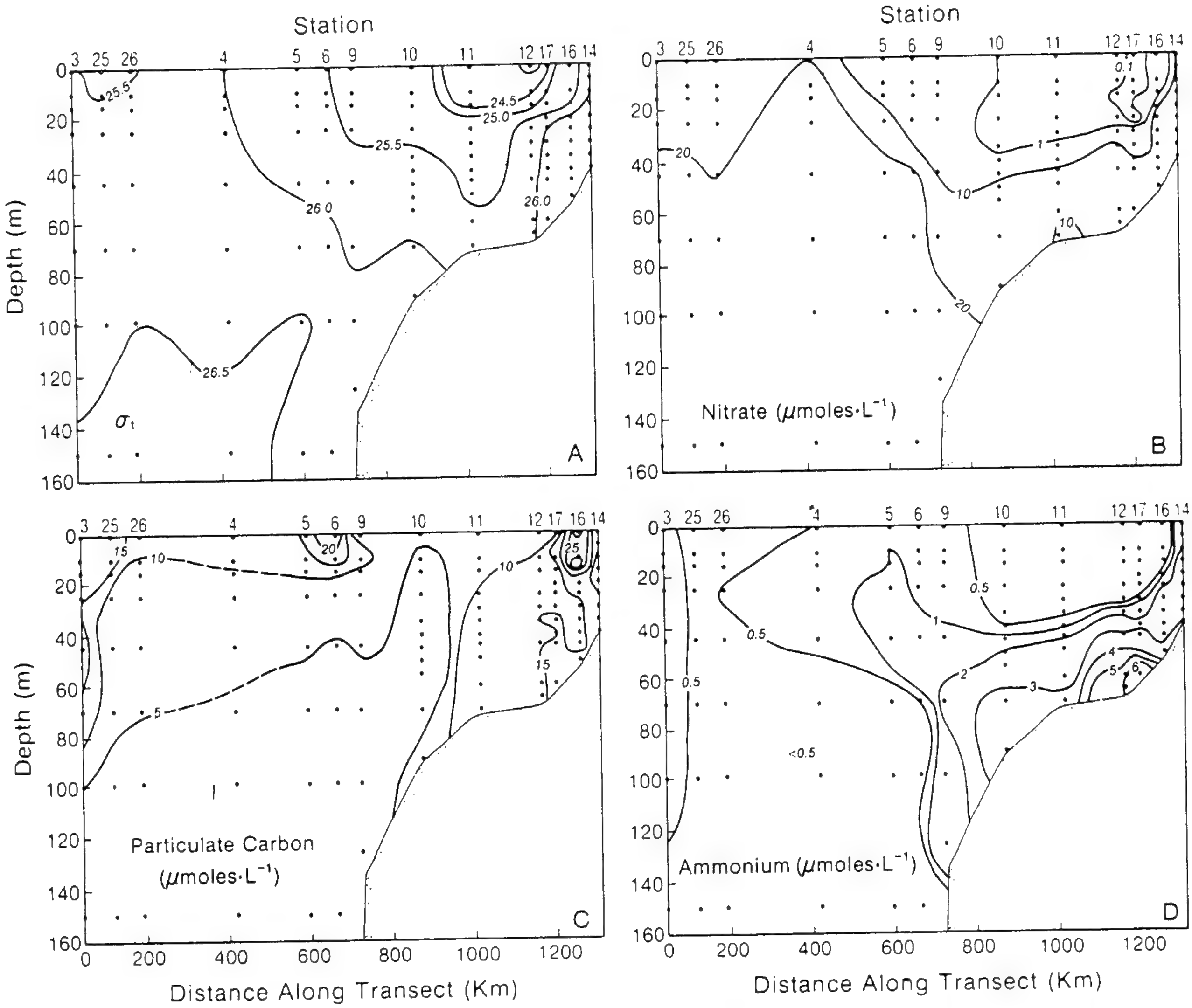

Fig. 2. Vertical distributions of sigma-t, nitrate, particulate carbon, and ammonium along a north-south transect in the Bering Sea.

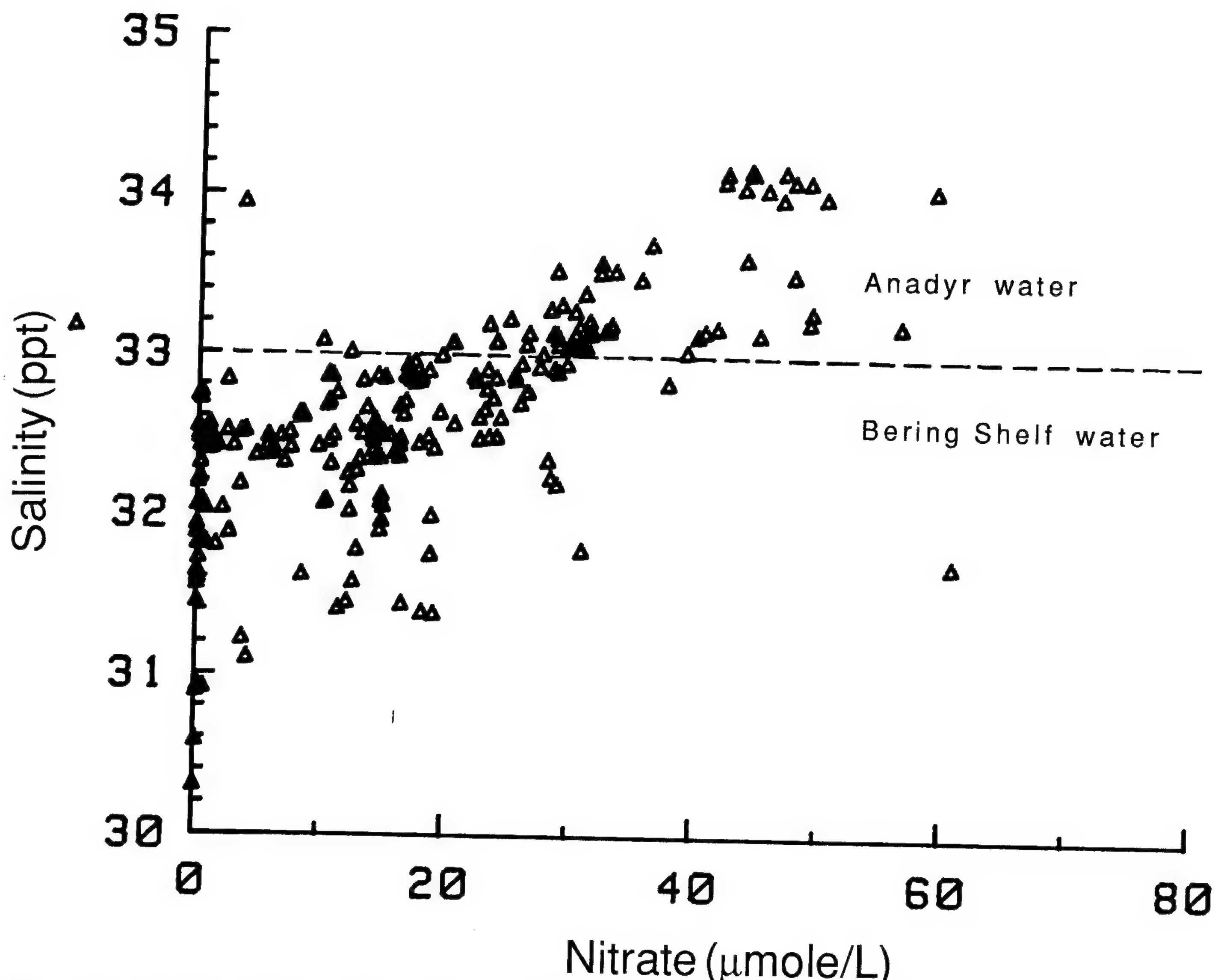

Fig. 3. Nitrate-salinity diagram for all samples collected at 500 m or less, 27 June-31 July 1984.

Regenerated nitrogen from marine degradation processes appears as ammonium, which allows a short-lived separation of newly regenerated and "older" nitrogen. The typical rate of nitrification by microbiota and high ammonium uptake by phytoplankton alter ammonium concentrations very rapidly, especially in the euphotic zone. Typical oceanic values of ammonium concentration were observed in the south polygon, but increased concentrations were present immediately below the pycnocline on the other three polygons (Fig. 4). The east polygon contained more than 1.5 μmole ammonium/L at a depth of 50 m, which has been observed to be the depth where ammonium concentrations from the middle shelf may be transported offshore (Whitledge et al. 1986). The north polygon also contained unusually large concentrations of ammonium (>4 μmole/L) in the near-bottom layer of about 10-m thickness. This small layer may be produced by decomposition processes for metabolism occurring in the sediments.

The waters with salinity below 31.5 ppt and greater than 33 ppt contained only small concentrations of ammonium (Fig. 5). The salinity range of 31.5 ppt to 33 ppt, where high ammonium values were observed, is typical for the central shelf water and it certainly represents in situ production of ammonium rather than transport from an external source. The largest concentration of ammonium observed in 1984 (6 μmole/L) appeared to result directly from the quantity of primary production that occurred during the spring bloom period and the subsequent vertical wind mixing of the water column.

A typical marine primary production and decomposition cycle of nitrogen will display an inverse relationship with oxygen. More specifically for ammonium, the decomposition processes that produce ammonium should consume oxygen; however, there are other factors that are occurring in the Bering Sea. The deep water in the south polygon, which contained low concentrations of oxygen, had converted ammonium to nitrate (Fig. 6), so that low oxygen and low ammonium occur together as in all deep sea environments. The large concentrations of ammonium produced on the central shelf as discussed above coexist with oxygen concentrations as high as 11.3 mL/L. Only a single sample of high-ammonium water contained less than 5 mL oxygen/L. Supersaturated oxygen did appear to decrease ammonium proportionally at the bottom of the pycnocline when both sufficient vertical stability and in situ light were present for phytoplankton growth.

Silicate

Dissolved silicon, which is necessary for diatom growth in the sea, was very plentiful in the south and east polygons, with concentrations greater than 25 μmole/L in the surface layer (Fig. 7). Maximum concentrations in the upper 200 m were about 60 μmole/L. The south polygon had smaller silicate concentrations between the depths 50 and 150 m, owing to its North Pacific Ocean origin. This substantiates previous observations that the Bering Sea has unusually large concentrations of silicate at depth (Park et al. 1975), and is shown in Fig. 8.

Diatom growth had reduced the surface silicate to less than 5 μmole/L in the north and west polygons. In the north polygon where the lowest dissolved silicon was observed, this was especially well correlated with chlorophyll and fucoxanthin pigments that are indicative of diatoms. Silicate was never depleted to a concentration that would limit diatom growth, but utilization lowered the values by about 10 μmole/L just below the pycnocline at station 15.

Phosphate

Orthophosphate concentrations, like nitrate and silicate, were highest in surface waters at the south and east polygons (Fig. 9), but the north and west polygons never had concentrations low enough to limit primary production.

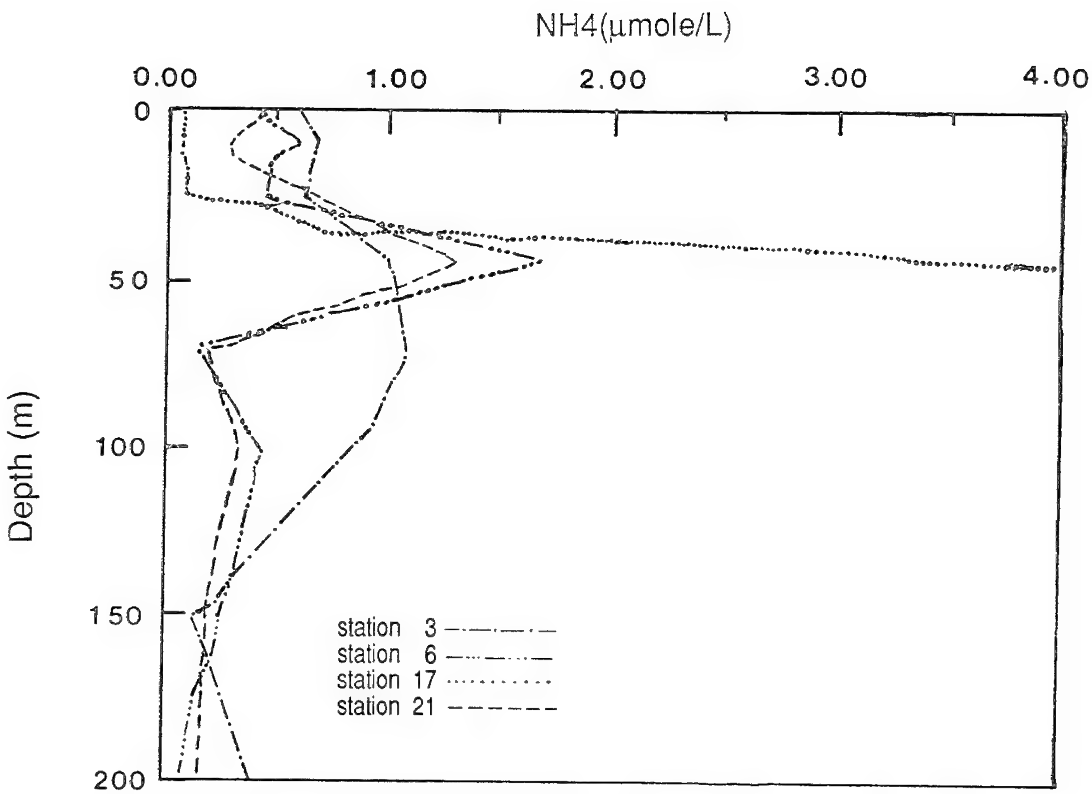

Fig. 4. Vertical distribution of ammonium concentration in the center of the polygons.

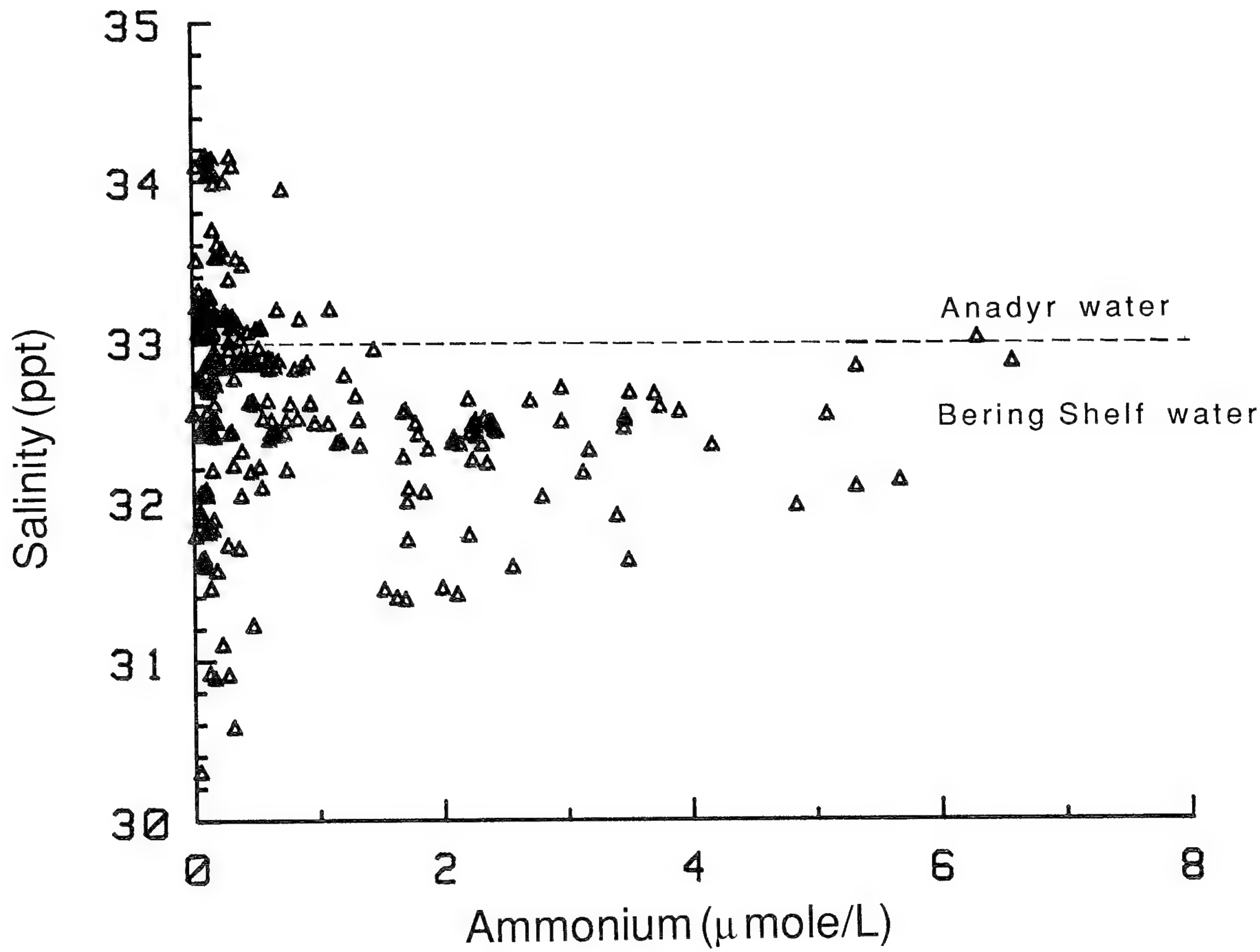

Fig. 5. Ammonium-salinity diagram for all samples collected at 500 m or less during 27 June-31 July 1984.

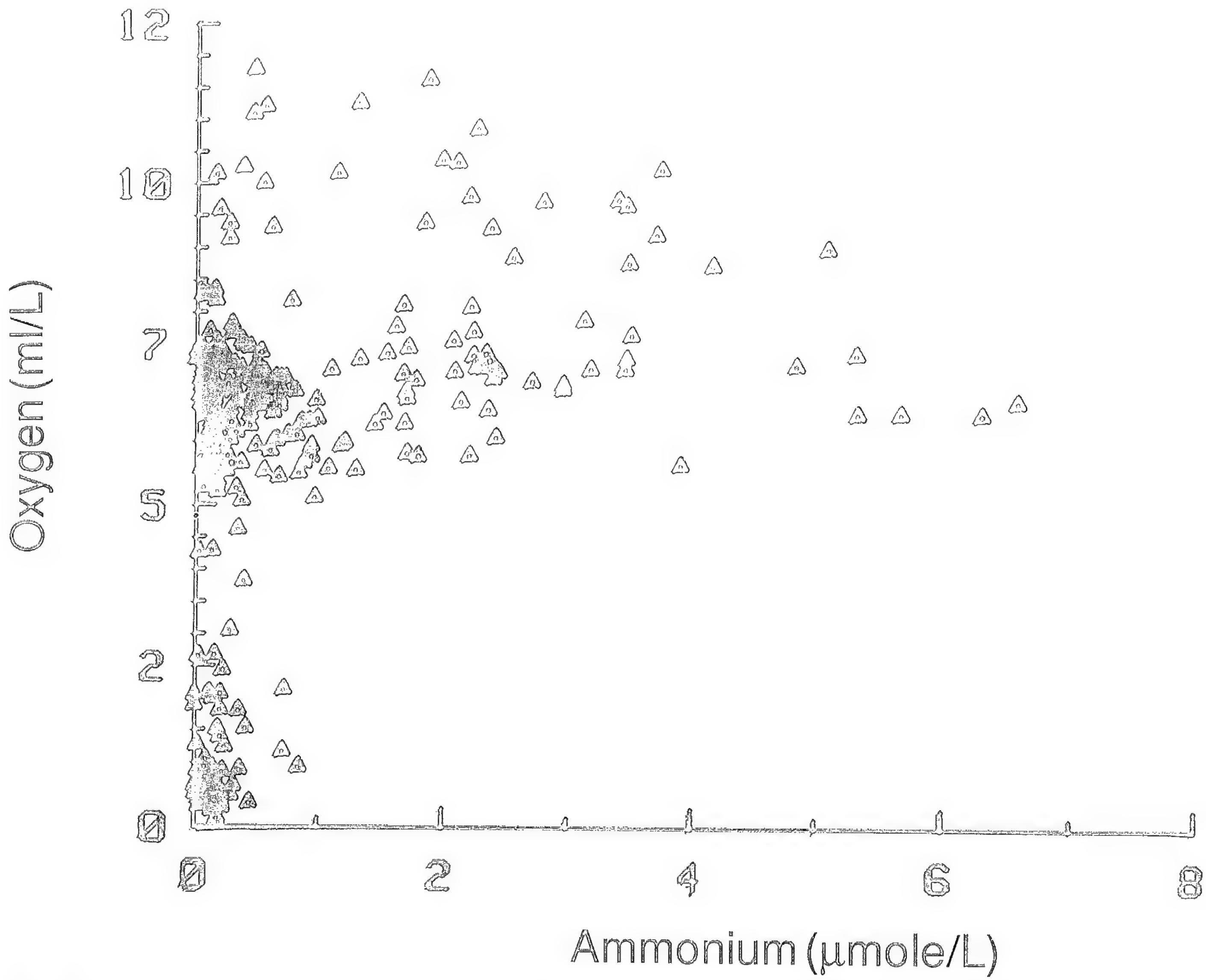

Fig. 6. Ammonium-oxygen diagram for all samples collected at 500 m or less during 27 June-31 July 1984.

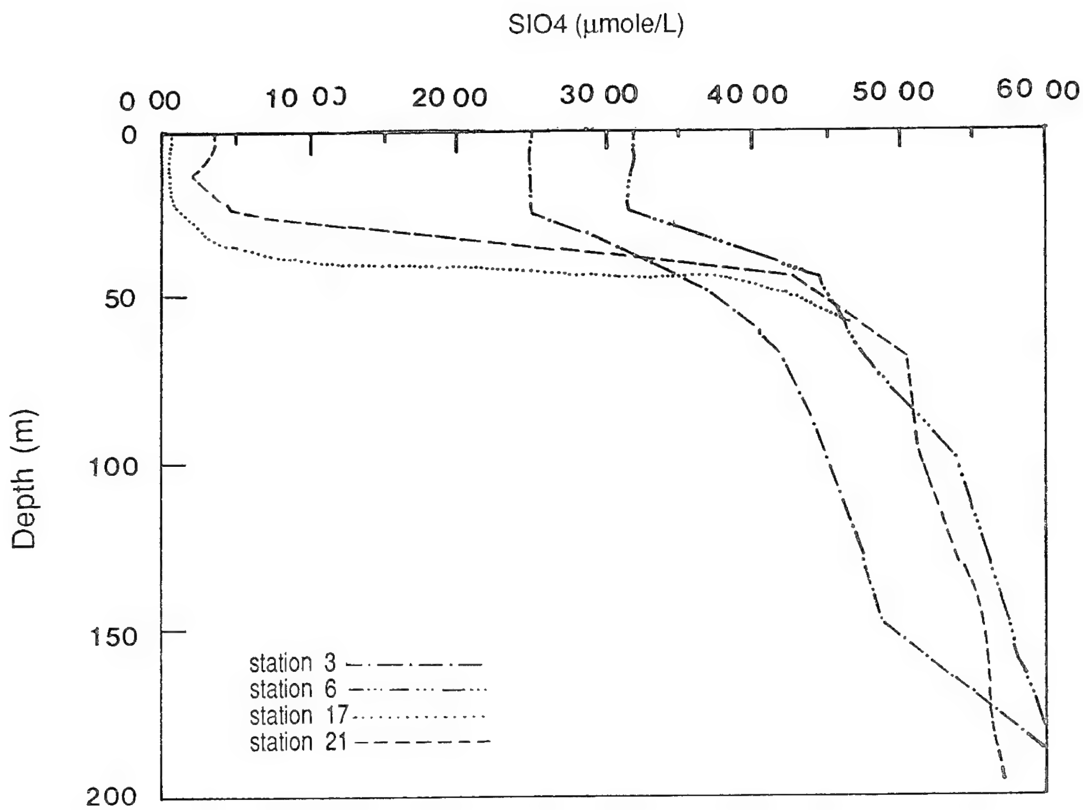

Fig. 7. Vertical distribution of silicate concentration in the center of the polygons.

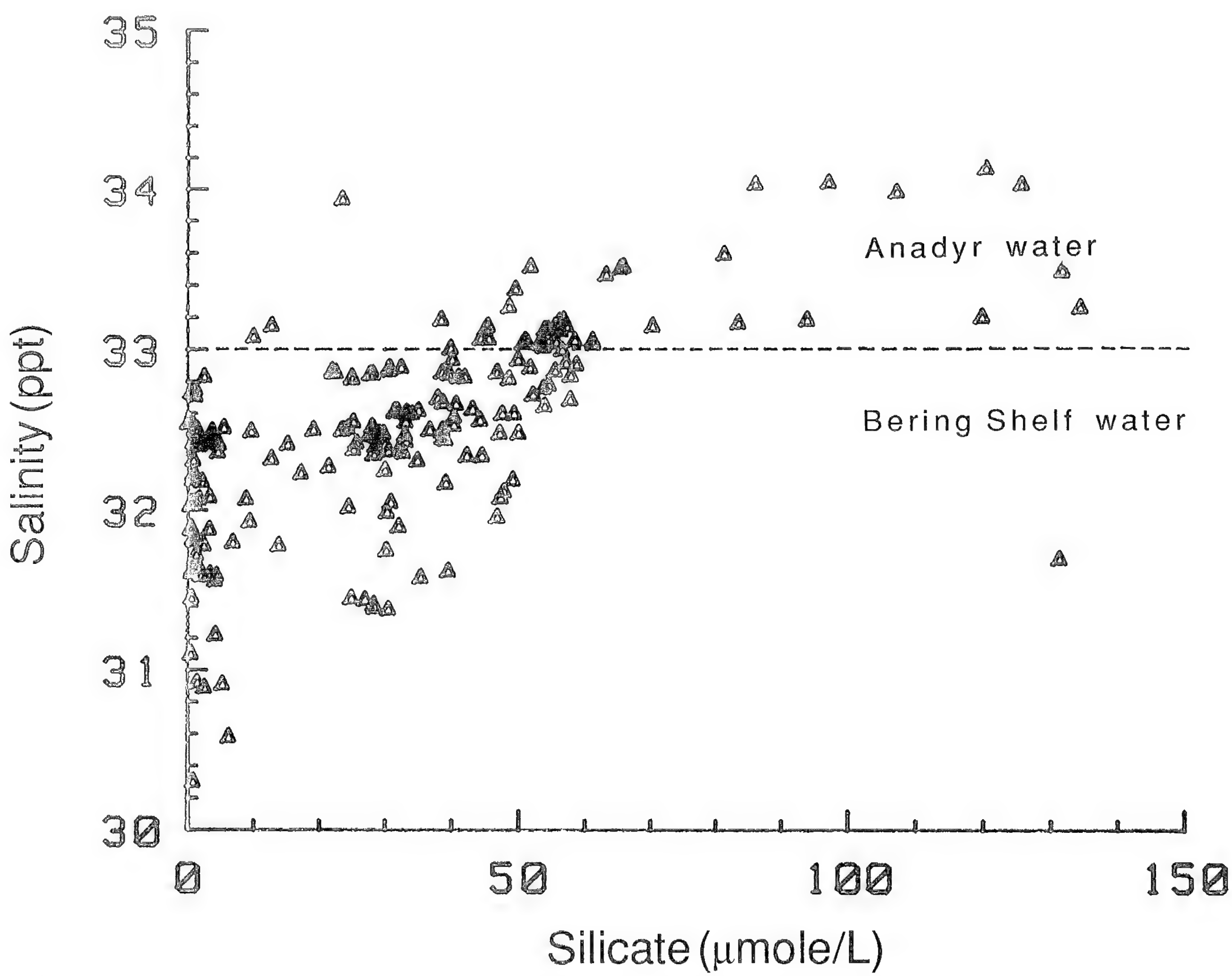

Fig. 8. Silicate-salinity diagram for all samples collected at 500 m or less, 27 June-July 1984.

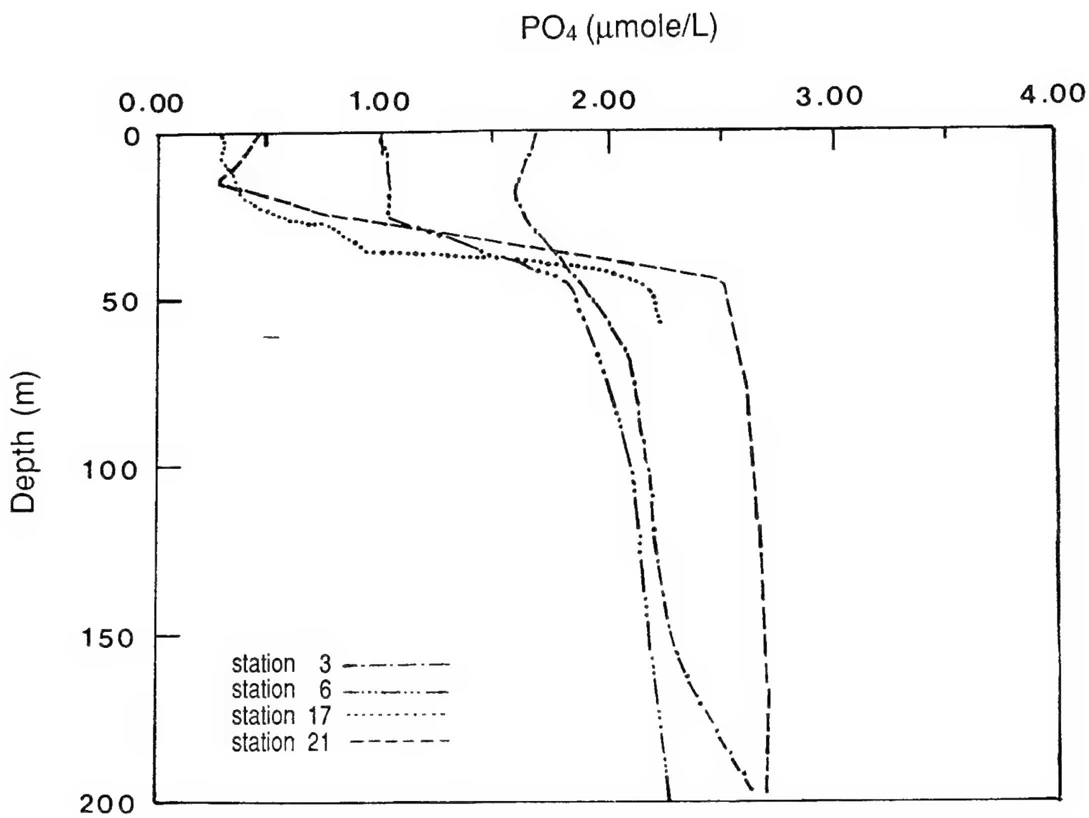

Fig. 9. Vertical distribution of phosphate concentration in the center of the polygons.

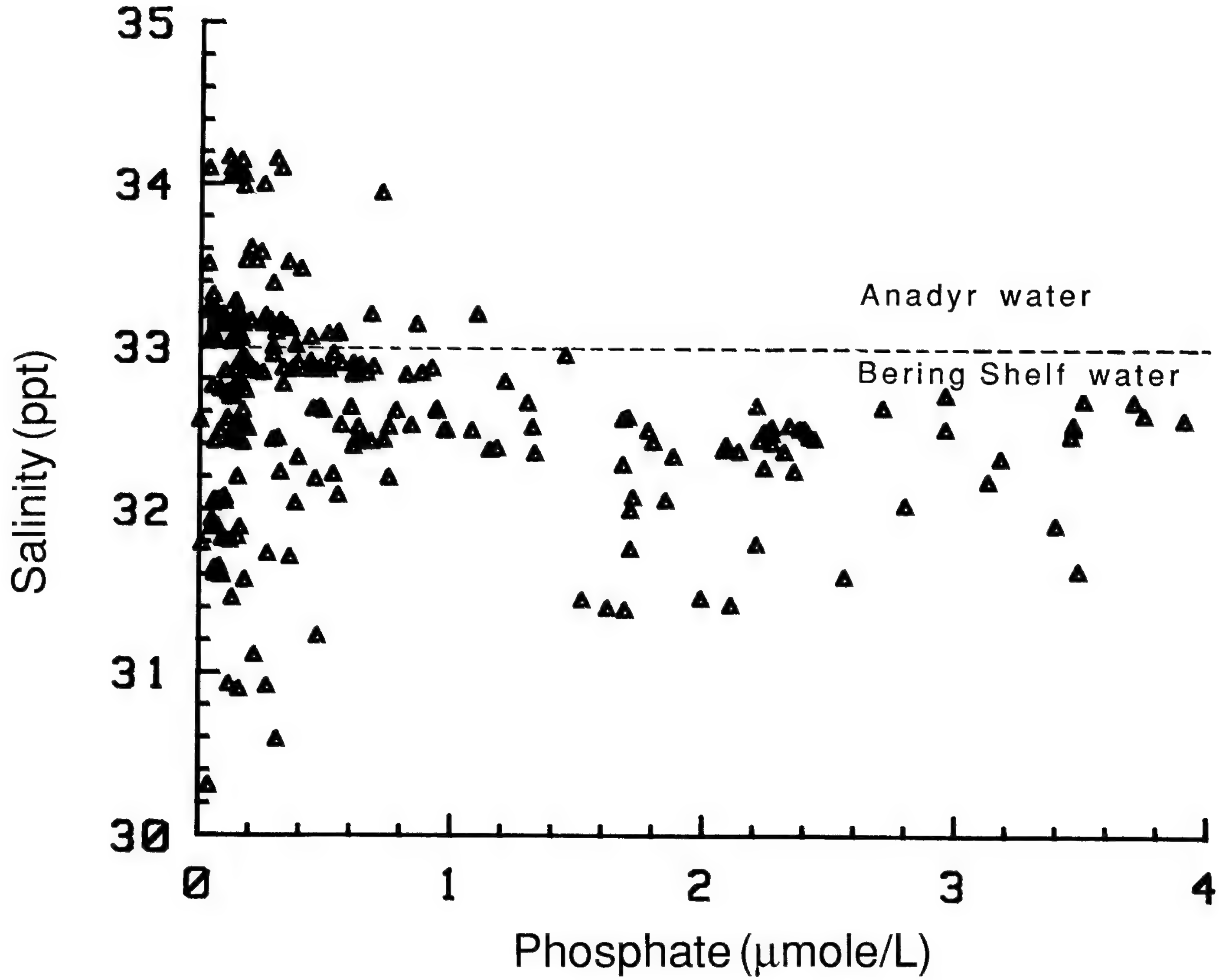

Fig. 10. Phosphate-salinity diagram for all samples collected at 500 m or less, 27 June-31 July 1984.

Phosphate concentrations between 50 and 150 m were lower on the south and east polygons. Phosphate concentrations ranged from 0.2 to more than 3 μmole/L, with the highest values located in waters with salinities near 34 ppt (Fig. 10). These values represent the highest concentrations found in the deep water of the Bering Sea basin.

Summary

The south and east polygons had substantial nutrient concentrations to support phytoplankton growth, while the north and west polygons contained only small concentrations of inorganic nutrients in the upper 30 m. The north and east polygons did contain elevated concentrations of ammonium below the pycnocline, which indicates that active regeneration of nitrogen was occurring. The deeper waters (>50 m) on the south, east, and west polygons contain large concentrations of nutrients, and the variations in those concentrations in each of the locations give some clues to the origin and recent history of those water masses.

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Biological Oceanography

PRIMARY PRODUCTION OF ORGANIC MATERIAL

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Located in a zone with rigorous climatic conditions, the Bering Sea is one of the most productive areas of the World Ocean, second only to the upwelling zones of the Pacific and Atlantic Oceans (Sorokin et al. 1983; Sambrotto et al. 1984; Tsyban et al. 1985). Research into the primary production of specific portions of the Bering Sea conducted by Soviet and American scientists, as well as by Japanese hydrobiologists, has shown that the level of primary production of organic substances in various areas of the sea can reach several grams of carbon organic material per square meter of the water column (Korsak 1982; Tsyban 1985). As a result of the great diversity in oceanic conditions, the size of primary production of organic substances at various periods of the seasonal succession of plankton communities can vary from 30 to 3,000 C m^{-2} day^{-1} (Sorokin 1973). Annual primary production of phytoplankton in the Bering Sea, according to the estimates of American and Soviet scientists, is approximately 200 million tons of organic material (Sambrotto et al. 1984; Tsyban 1985). Despite the comparatively large number of scientific expeditions, the central and the northwest portions of the Bering Sea have not been sufficiently studied with respect to the rate of production of new organic substances.

In July-August 1984 aboard the RV *Akademik Korolev*, scientists carried out a comprehensive U.S.-U.S.S.R. expedition to analyze the conditions of the Bering Sea ecosystem and to determine human influence on natural change.

Materials and Methods

The work of this expedition was carried out in four polygons that were located in various areas of the Bering Sea and along transects between the polygons under study (frontispiece). The distribution of the polygons fully corresponded to their positions during work carried out in the previous expedition in the Bering Sea in 1981 aboard the research vessel *Akademik Shirshov* (Tsyban 1985). Probes for the determination of primary production of phytoplankton were taken from depths of 0.5, 5, 10, 15, 25, and 45 m. The primary production was determined through the radio carbon method of modification developed by Yu.I. Sorokin (Tsyban 1985; Tsyban et al. 1985). At each station, we determined photosynthesis in the samples of water taken from the surface (the coefficient of photosynthesis and the coefficient of Kr) showing the dependence of the intensity of photosynthesis on the distribution of phytoplankton along a vertical axis. Several times during the cruise, we determined the dependence of the intensity of photosynthesis in the water column on light (the coefficient Kt), as well as the dependence of photosynthesis on the time of day. These determinations permitted the calculations of coefficients necessary to determine the production of phytoplankton during each daylight period. In order to determine content of carbon in a wet mass of substances of phytoplankton the estimate of 10 percent was used (Sorokin et al. 1983). The biomass of phytoplankton was calculated using data from the determination of the concentration of

chlorophyll *a*, which was obtained by the American specialists during the expedition. The content of chlorophyll *a* in a raw mass of phytoplankton was equivalent to 0.3% (Sorokin et al. 1983).

The determination of the radioactivity of filters of ^{14}C for phytoplankton were conducted by using scintillation on a Mark-2 calculator and using the scintillators GS-106 and GS-8 (Sorokin 1973; Tsyban 1985).

Research Results

According to our data, primary production in the south polygon varied from 73 to 316 mg C m^{-2} day $^{-1}$, with an average level of production equivalent to 190 mg m^{-2} day^{-1} (Table 1). The level of phytoplankton biomass varied from 11.5 to 23 g of raw mass of organic substance. The size of the P/B coefficient, which characterizes the degree intensity of photosynthesis in units of biomass of phytoplankton, consisted on the average of 0.11 with a coefficient of variability from 0.06 to 0.14, for three stations in the south polygon.

The results of the determination of the phytoplankton production and the size of the P/B coefficients attest to relatively low levels of new formation of organic materials in the south polygon during the transitional period of seasonal succession of the plankton community from biological spring to biological summer. Station 4, located along the transect, showed primary production twice as large as the south polygon.

At stations in the east polygon, primary production varied from 160 to 960 mg C m^{-2} day^{-1}, with an average level of 430 mg C m^{-2} day^{-1}, that is, approximately 2.5 times more as much as that in the south polygon (Table 1). Significant phytoplankton biomass at the east consisted of 10 grams. The size of P/B coefficients in this polygon varied from 0.2 to 1.1, with an average 0.48. It should be noted that a tendency towards increasing production and biomass of microalgae was observed also along transect number 1, during movement of the ship from the south polygon to the east polygon (frontispiece; Table 1).

As the ship moved from the east to the north polygon, the nutrient content in the water layer from 0 to 45 increased significantly, according to the data determined by another participant in the joint expedition (see Whitledge papers in this report). At the same time there was also an increase in the biomass and the production of phytoplankton in the zone of photosynthesis.

Thus, at station 10 along the second transect, the maximum amount of primary production of organic substances was found. This was 4,800 mg C m^{-2} day^{-1}, and there were also high values for P/B coefficients (Table 1).

The primary production in the north polygon, which was located to the west of St. Lawrence Island, varied from 200 to 4,400 mg C m^{-2} day^{-1} (Table 1), and on the average consisted of 1,950 mg C m^{-2} day^{-1} of primary production of organic substances. Primary production of phytoplankton at various stations of this polygon had almost the same high variability discovered during the 1981 expedition aboard the *Akademik Shirshov* (Tsyban et al. 1985). Such high values for primary production in this area of the ocean can be explained, it would appear, by the presence of constant upwelling around St. Lawrence Island. This intensive primary production of the new organic substances at the stations of the north polygon is evident in the significant P/B coefficients. At stations 18 and 19, located to the southwest of the north polygon, the level of primary production varied from 306 to 1,050 mg C m^{-2} day^{-1} (Table 1).

In contrast to the north polygon, the west polygon was significantly lower in the production of phytoplankton and varied to a lesser degree at the different stations. Thus the production in the west polygon varied from 355 to 720 mg C m^{-2} day^{-1}, the biomass of

Table 1. *Values for primary production (P), phytoplankton biomass (B), and P/B coefficients (for the photosynthesis layer to 35 m).*

Station	P (mg c m^{-2} day^{-1})	B raw organic material (g m^{-2} day^{-1})	P/B
South polygon			
1	73	11.5	0.06
2	316	23.4	0.14
25	180	12.7	0.14
26	-	6.0	-
East polygon			
5	960	8.8	1.1
6	170	12.7	0.13
8	160	7.9	0.2
9	-	10.1	-
10	4,800	4.7	10.2
North polygon			
12	860	4.1	2.1
13	3,700	51.0	0.7
14	4,400	40.0	1.1
15	200	5.5	0.36
17	555	5.1	1.1
18	306	-	-
19	1,050	-	-
West polygon			
20	720	10.5	0.7
21	480	9.0	0.5
22	706	10.5	0.7
23	355	8.0	0.45

from 355 to 720 mg C m^{-2} day^{-1}, the biomass of phytoplankton from 8 to 10.5 g of raw mass, and the size of the P/B coefficients from 0.45 to 0.7 (Table 1).

Comparing the production of phytoplankton in the various polygons of the Bering Sea in 1981 and 1984 we may conclude the following: in the north polygon, and for a significant distance around it, the level of productivity completely corresponds to the level of productivity in areas of upwelling; when water rises from the deep part of the sea in this area, there is a comparatively large quantity of nutrients, as well as low water temperatures.

The depth of the photosynthetic zone in the Bering Sea during the period of research in the 1984 expedition never exceeded 45 m. Vertical profiles of primary production of organic substances usually had one maximum, which was located in the zone of optimal light conditions at depths of 5-10 m, and more rarely in the surface waters. Below this maximum, production of phytoplankton fell off right down to the lowest levels of photosynthesis (Fig. 1).

Thus, research in primary production of organic substances in July 1984 attests to the high biological productivity of the Bering Sea ecosystem. The results obtained show the presence of a constant upwelling during the summer period in the area not far from St. Lawrence Island. Comparison of average values from 1981 and 1984 for primary production calculated for the south, west, and east polygons shows a high degree of consistency of the processes of new formation of organic substances between the two years in these areas of the Bering Sea and characterizes this basin as a highly productive ecosystem (Tsyban 1985).The average values for the P/B coefficients, calculated for various polygons (0.5-2.6), showed the transitional status of the plankton community of the Bering Sea during the period of our research, from biological summer to biological fall.

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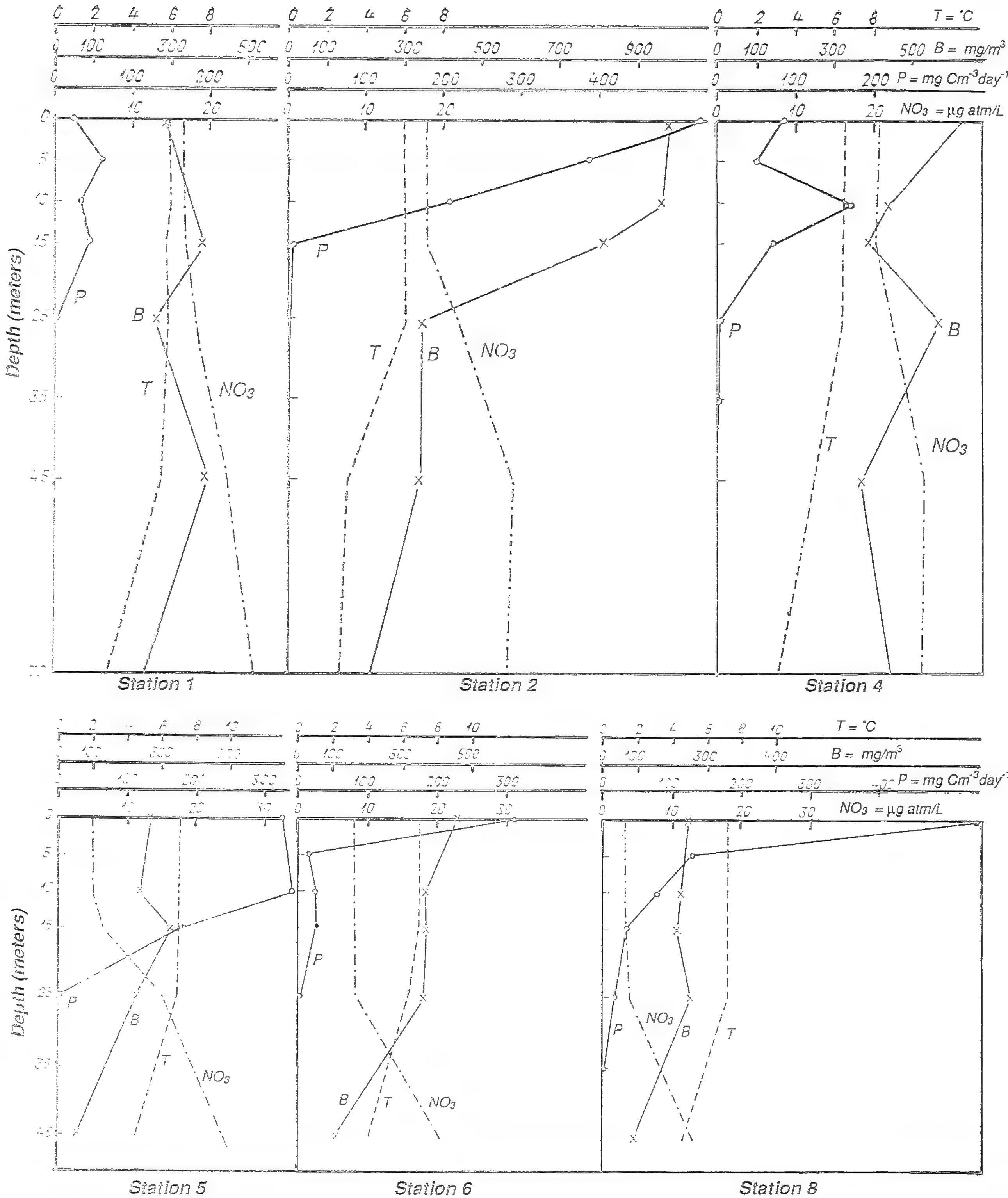


Fig. 1. Vertical distribution of temperature (T=°C), Nitrates (NO_3=μg atmosphere/L), phytoplankton biomass (B=mg/m^3) and primary production (P=mg C m^{-2} day^{-1}) at stations in the Bering Sea.

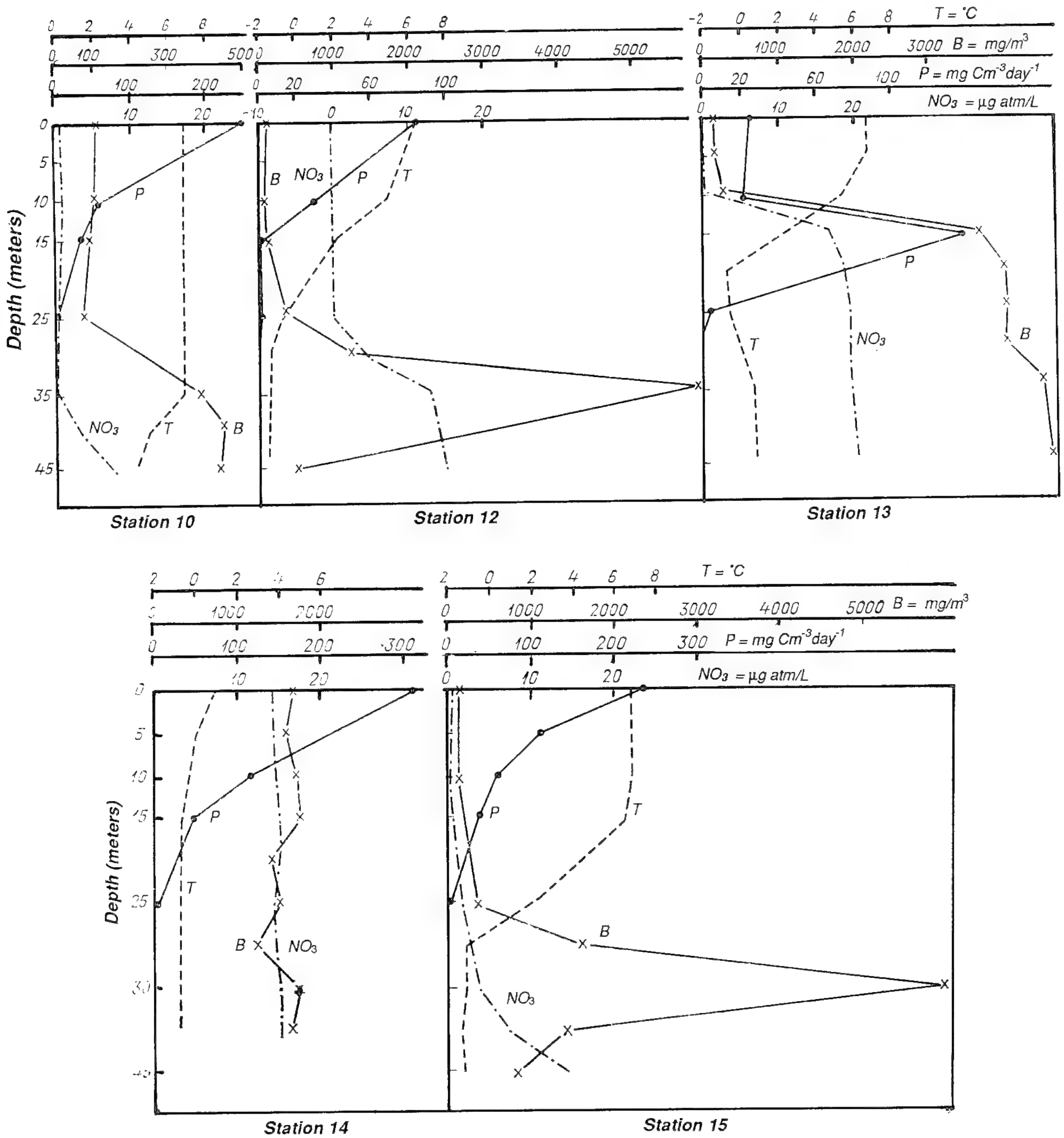
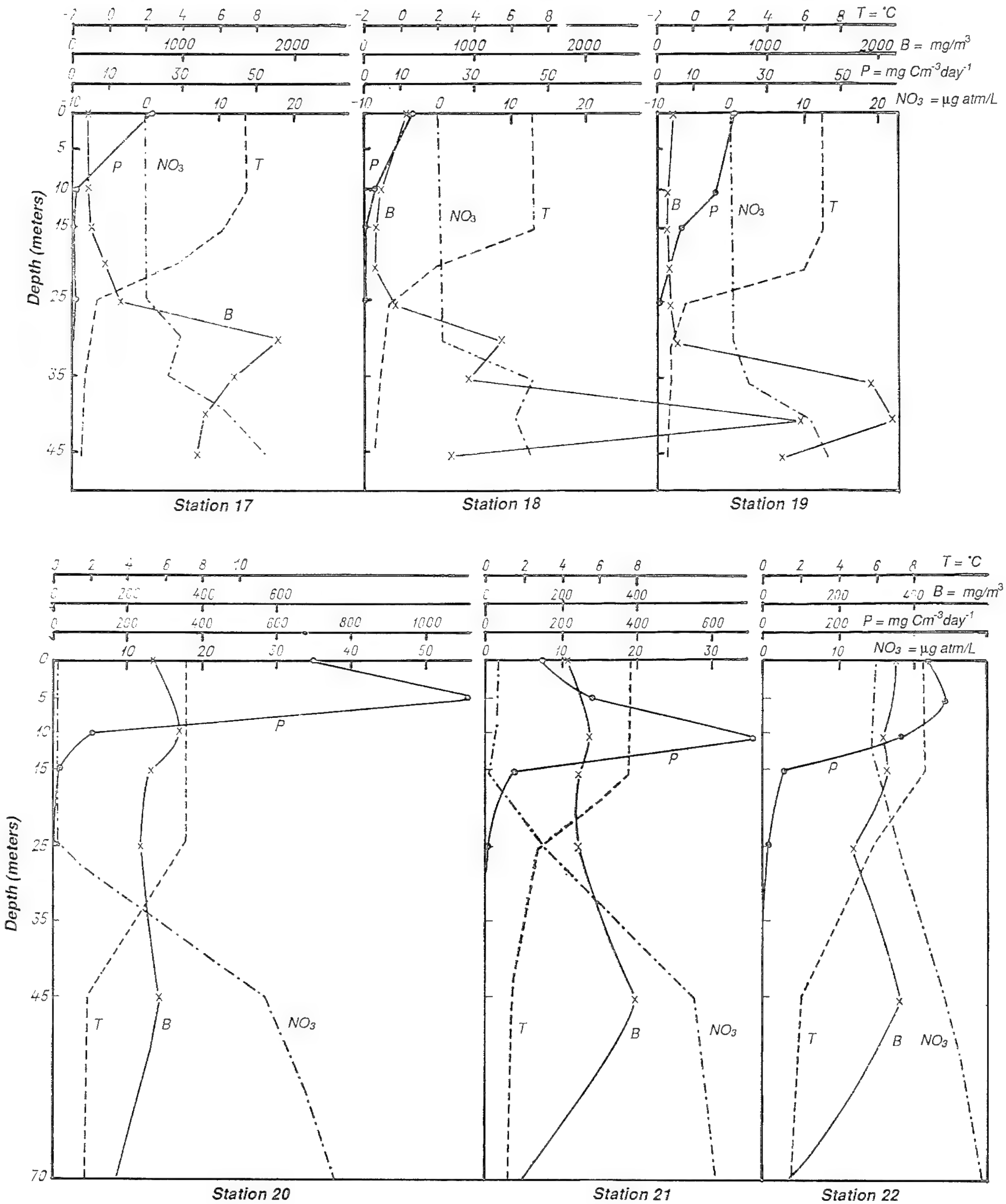


Fig. 1. Continued.



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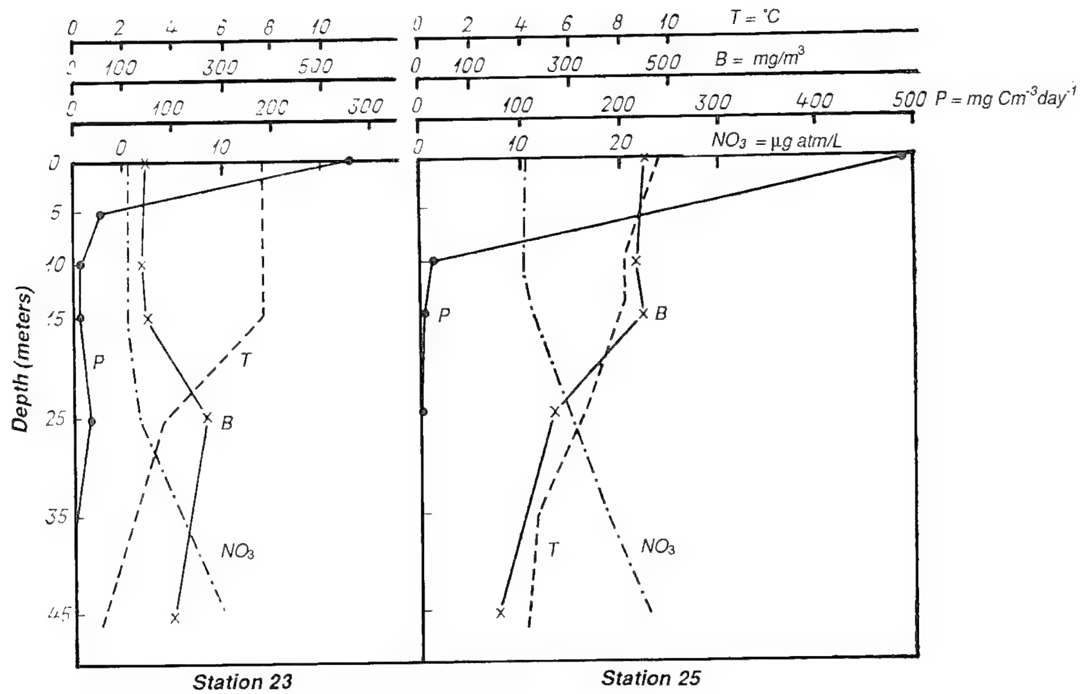

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MODELING PRIMARY PRODUCTION IN THE BERING SEA

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Introduction

The Bering Sea is an impressive fishery ground for a multitude of species (Hood and Kelly 1974). It is the largest source of Pacific pollock, producing an estimated annual yield of 1.1 million metric tons (Washburn and Weller 1986). The food webs in the region are not very well studied because of inclement weather, large area, political boundaries, migration patterns of animals in and out of the region, and other factors. This study was performed to improve understanding of the photosynthetic activities of phytoplankton in their role as the base of trophic webs in the Bering Sea.

During the second joint American-Soviet expedition in the Bering Sea, data were collected in an interdisciplinary fashion (Whitledge et al., in press). These data corroborate and extend recent findings of high primary production in the Bering Sea (Koike et al. 1982; Sambrotto et al. 1984; Sambrotto et al. 1986). While very good temporal coverage was obtained in some cases, most of the previous work on production in the Bering Sea has been limited to certain portions of the basin. The binational nature of this project made sampling possible throughout the Bering Sea, thus affording better spatial estimates for productivity in this region.

This paper presents the results of a series of calculations used to model the productivity vs. depth relationships found in the Bering Sea. Furthermore, the data gathered during the cruise provide estimates of physiological parameters that may be used in conjunction with remote sensing to estimate productivity.

Materials and Methods

Samples were collected at 26 stations throughout the Bering Sea during July 1984. Twenty of these stations were grouped into four five-station polygons. These four polygons were designated north, south, east, and west, denoting their relative position (frontispiece). The five stations of a polygon served as replicate samples for a given region. The remaining six stations were located between the polygons.

Sampling for the primary production experiments is described by Zeeman and Jensen (in this report). Briefly, photosynthetic rates were measured with phytoplankton from two depths at each station. One sample was collected from the surface waters, the other from below the thermocline (in the chlorophyll maximum where applicable). Sampling was performed with non-metallic Niskin bottles on a Kevlar wire.

Photosynthetic rates were determined at eight light intensities, using an on-deck incubator at near-sea-surface temperatures. Photosynthesis was determined by ^{14}C uptake (Strickland and Parsons 1972) in acid-washed

polycarbonate flasks. Incubations lasted one hour, after which samples were filtered through 0.4-μm pore-size filters. Determination of activity on the filters was by liquid scintillation counting.

Photosynthesis-irradiance relationships (P-I parameters) were determined by nonlinear least-squares regressions, using the hyperbolic tangent function (Jassby and Platt 1976; Platt et al. 1980).

Irradiance data was measured with a Li-Cor integrating quantum meter (photosynthetically active radiation, PAR) for continuous on-deck measurements, and a Li-Cor quantum meter (PAR) with a submersible quantum sensor for measuring submarine light fields.

Chlorophyll was extracted in acetone and measured fluorometrically (Whitledge et al., in press). In addition, in situ chlorophyll fluorescence was determined continuously with a flow-through fluorometer. Temperature profiles were determined by expendable bathythermographs (XBT) and reversing thermometers. Water chemistry was performed by autoanalyzer (Whitledge et al., in press).

The photosynthesis vs. depth relationship was modeled by taking the P-I parameters and calculating photosynthetic rates at 1-m intervals throughout the water column. Summation of these values provided areal production estimates. The model also computed production at 1-h intervals throughout the day and summed these values to arrive at daily production values. The light intensities used in these calculations were derived from records of the on-deck sensor, corrected for surface reflection, and estimated for each depth by using the measured extinction coefficient at that station. When necessary, the P-I parameters used in the calculations were changed to reflect differences between surface and deep-living populations. For the model, the depth at which such a change in parameters occurred was the thermocline. The extinction coefficient was also depth variable in the model.

Computations of photosynthesis vs. depth were made by using a FORTRAN program on a Prime minicomputer. Statistical analyses were made by using BMDP (Dixon 1975) on a Prime minicomputer and SYSTAT (Wilkinson 1986) on an IBM AT clone.

Results

Table 1 lists chlorophyll (mg Chl/m^3), productivity rate (mg C m^{-3} h^{-1}), and irradiance (μE/m^2/s) for standard depths used in other analyses on the cruise. The data are listed by station as well as polygon number. Polygon 1 is the southern polygon, 2 the eastern, 3 the northern, and 4 the western. Polygon 5 is not a single area, but consists of all the intermediate transect stations. These data represent only partial output from the productivity model. The model output itself is summarized in Fig. 1, showing the hourly and daily areal production (mg C m^{-2} h^{-1} or mg C m^{-2} d^{-1}). The hourly rates are those at the time of maximum light intensity during the day.

Mean hourly production in the Bering Sea was estimated as 84.5 $\pm$ 108.8 mg C m^{-2} h^{-1}; while daily rates averaged 0.9 $\pm$ 1.3 g C m^{-2} d^{-1}. Extinction coefficients were low throughout the region, with three exceptions (stations 13, 14, and 16). The mean extinction coefficient for PAR was 0.11 $\pm$ 0.05. This meant that the average depth of the 1% light intensity was about 47 m. Extinction coefficients (K) and depths of the 1% light level (201) are presented in Fig. 2. There was, however, no clear relation between either of these measures and the production rates (Fig. 3).

The data were subjected to Bartlett's test for homogeneity of variances and failed. Plots of the data showed that three stations had extreme values for the extinction coefficient

Table 1. *Chlorophyll concentration, productivity rates, and light intensity at Bering Sea locations, June-July 1984.*

Station	Depth (m)	Chlorophyll concentration (mg/m^3)	Productivity rate (mg C m^{-3} h^{-1})	Light intensity (μE m^{-2} s^{-1})	Polygon
1	0	0.44	1.024	177.00	1
1	10	0.61	0.883	62.00	1
1	25	0.40	0.142	16.00	1
1	45	0.62	0.060	3.00	1
2	0	1.67	3.140	604.00	1
2	10	1.20	2.310	211.00	1
2	15	1.38	2.330	130.00	1
2	25	0.48	2.160	52.00	1
2	45	0.11	0.070	11.00	1
3	0	0.81	2.240	538.00	1
3	10	0.70	1.990	188.00	1
3	25	0.79	1.660	50.00	1
3	45	0.63	0.430	9.00	1
3	70	0.25	0.170	1.00	1
4	0	0.79	1.810	155.00	5
4	10	0.64	1.040	49.00	5
4	15	0.97	0.860	26.00	5
4	25	0.62	0.270	12.00	5
4	45	0.75	0.008	2.00	5
5	0	0.44	1.590	435.00	2
5	10	0.39	1.490	185.00	2
5	15	0.55	1.830	115.00	2
5	25	0.36	0.780	40.00	2
5	45	0.05	0.050	10.00	2
5	70	0.01	0.000	1.70	2
6	0	0.77	1.880	502.00	2
6	10	0.60	1.390	193.00	2
6	15	0.61	1.770	114.00	2
6	25	0.60	0.800	39.00	2
6	45	0.14	0.070	5.00	2
6	70	0.01	0.002	0.30	2
7	0	0.55	2.490	646.00	2
7	10	0.42	1.700	183.00	2
7	15	0.48	1.200	91.00	2
7	25	0.53	0.560	34.50	2
7	45	0.18	0.080	5.00	2
8	0	0.38	1.670	671.00	2
8	10	0.35	1.180	252.00	2
8	15	0.33	0.840	146.00	2

Table 1. *Continued.*

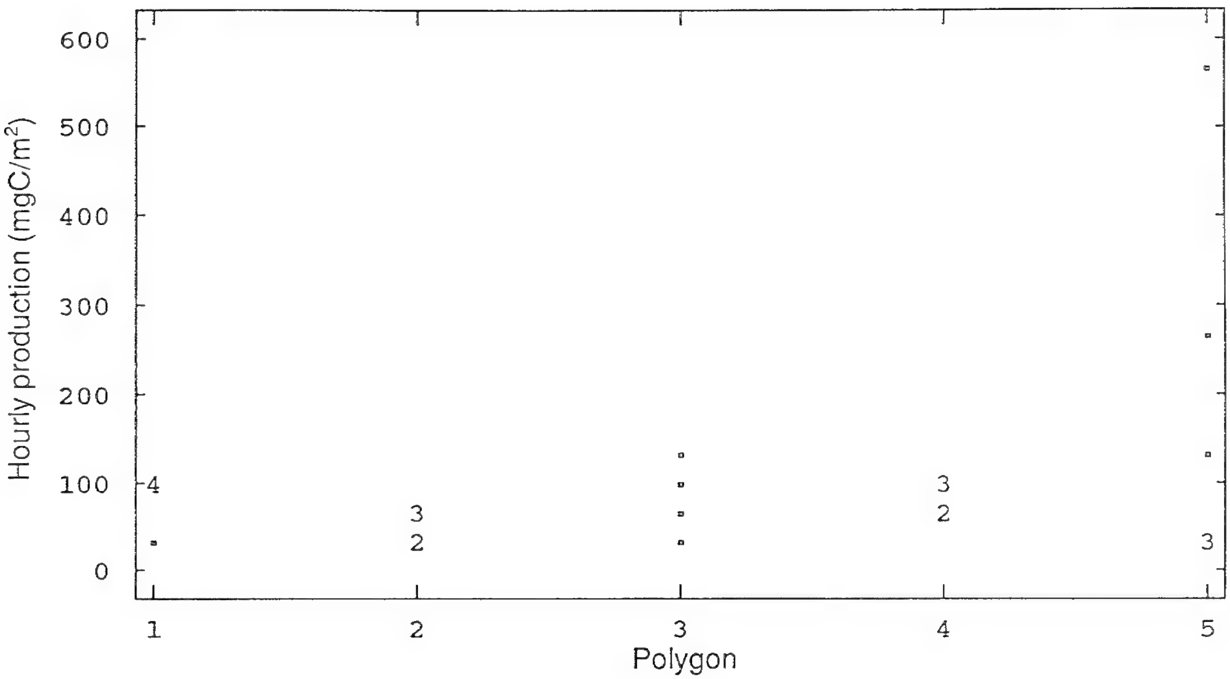
Station	Depth (m)	Chlorophyll concentration (mg/m^3)	Productivity rate (mg C m^{-3} h^{-1})	Light intensity (μE m^{-2} s^{-1})	Polygon
8	25	0.40	0.450	49.00	2
9	0	0.57	0.930	619.00	2
9	10	0.49	0.790	273.00	2
9	15	0.44	0.690	173.00	2
9	25	0.40	0.380	70.00	2
9	45	0.55	0.210	10.00	2
9	75	0.23	0.000	0.70	2
10	0	0.16	0.610	616.00	5
10	10	0.15	0.540	264.00	5
10	15	0.12	0.370	165.00	5
10	25	0.09	0.130	59.00	5
10	45	0.71	0.070	9.00	5
10	50	0.60	0.070	6.00	5
11	0	0.21	0.260	616.00	5
11	10	0.61	0.690	264.00	5
11	15	0.21	0.320	150.00	5
11	25	0.85	2.040	59.00	5
11	30	5.92	9.630	37.00	5
11	35	4.84	6.640	23.00	5
11	45	0.48	0.330	9.00	5
11	50	0.31	0.030	6.00	5
12	0	0.21	0.360	980.00	3
12	10	0.14	0.250	420.00	3
12	15	0.18	0.300	263.00	3
12	25	0.57	0.440	60.00	3
12	30	21.60	7.120	30.00	3
12	35	6.01	1.530	15.00	3
12	45	0.75	0.000	4.00	3
13	0	0.22	0.580	1097.00	3
13	10	0.30	0.730	316.00	3
13	15	6.46	11.360	159.00	3
13	20	7.00	5.440	20.30	3
13	25	7.36	1.240	5.00	3
13	30	7.00	0.125	0.90	3
14	0	2.91	37.080	840.00	5
14	5	2.75	36.080	353.00	5
14	10	2.91	29.200	112.00	5
14	15	3.00	12.090	36.00	5
14	20	2.36	8.640	10.00	5
14	25	2.50	2.960	3.00	5

Table 1. *Continued.*

Station	Depth (m)	Chlorophyll concentration (mg/m^3)	Productivity rate ($mg\ C\ m^{-3}\ h^{-1}$)	Light intensity ($\mu E\ m^{-2}\ s^{-1}$)	Polygon
14	30	1.96	0.910	1.00	5
14	35	2.87	0.520	0.30	5
15	0	0.29	0.450	1095.00	3
15	10	0.26	0.400	650.00	3
15	15	0.34	0.490	486.00	3
15	20	-	0.100	307.00	3
15	25	0.54	0.125	193.00	3
15	30	2.74	0.467	122.00	3
15	35	10.40	1.910	77.00	3
15	40	2.36	0.699	44.50	3
15	45	1.31	0.190	31.00	3
15	50	0.16	0.030	17.70	3
16	0	8.53	4.070	729.00	3
16	10	5.29	5.270	53.00	3
16	15	13.30	2.890	9.00	3
16	20	4.01	0.830	4.00	3
16	25	3.09	0.000	1.00	3
18	0	0.64	0.307	1148.00	5
18	10	0.19	0.109	510.00	5
18	15	0.13	0.060	325.00	5
18	25	0.39	0.080	132.00	5
18	45	1.27	0.436	22.00	5
19	0	0.23	0.364	1070.00	5
19	10	0.14	-	-	-
19	25	0.12	0.160	220.00	5
19	30	0.23	0.884	163.00	5
19	35	3.36	11.500	117.00	5
19	40	3.68	14.120	84.86	0
19	50	2.50	7.100	44.00	5
19	50	-	3.900	32.00	5
19	60	0.32	1.000	23.10	5
20	0	0.44	2.010	771.00	4
20	10	0.55	2.410	396.00	4
20	15	0.43	1.990	273.00	4
20	25	0.38	1.430	130.00	4
20	35	-	1.020	62.00	4
20	45	0.47	0.540	29.70	4
20	70	0.26	0.030	4.60	4
21	0	0.33	1.890	386.00	4
21	10	0.45	2.350	183.00	4

Table 1. *Continued.*

Station	Depth (m)	Chlorophyll concentration (mg/m^3)	Productivity rate (mg C m^{-3} h^{-1})	Light intensity (μE m^{-2} s^{-1})	Polygon
21	15	0.39	1.930	121.00	4
21	25	0.66	1.750	53.00	4
21	45	0.14	0.157	10.00	4
21	70	0.06	0.002	1.26	4
22	0	0.57	2.200	683.00	4
22	10	0.52	2.050	280.00	4
22	15	0.55	1.960	171.00	4
22	25	0.38	0.830	63.50	4
22	45	0.61	0.460	8.70	4
22	70	0.09	0	0.74	4
23	0	0.22	1.460	679.00	4
23	10	0.20	1.300	250.20	4
23	15	0.22	1.220	144.00	4
23	25	0.43	1.040	47.00	4
23	45	0.31	0.160	5.00	4
23	70	0.14	0	0.32	4
24	0	0.35	1.630	766.00	4
24	10	0.73	3.440	344.00	4
24	15	0.31	1.930	220.00	4
24	25	0.41	1.180	81.00	4
24	45	0.31	0.430	11.00	4
24	70	0.05	0	0.90	4
25	0	0.77	4.090	673.00	1
25	10	0.73	3.770	237.00	1
25	15	0.75	3.250	133.00	1
25	25	0.43	1.160	61.00	1
25	45	0.24	1.040	12.00	1
25	70	0.08	0.350	2.00	1
26	0	0.28	0.645	770.00	1
26	10	0.25	0.550	382.00	1
26	15	0.24	0.470	258.00	1
26	25	0.26	0.300	118.00	1
26	45	0.38	0.185	25.00	1
26	70	0.28	0.027	3.50	1



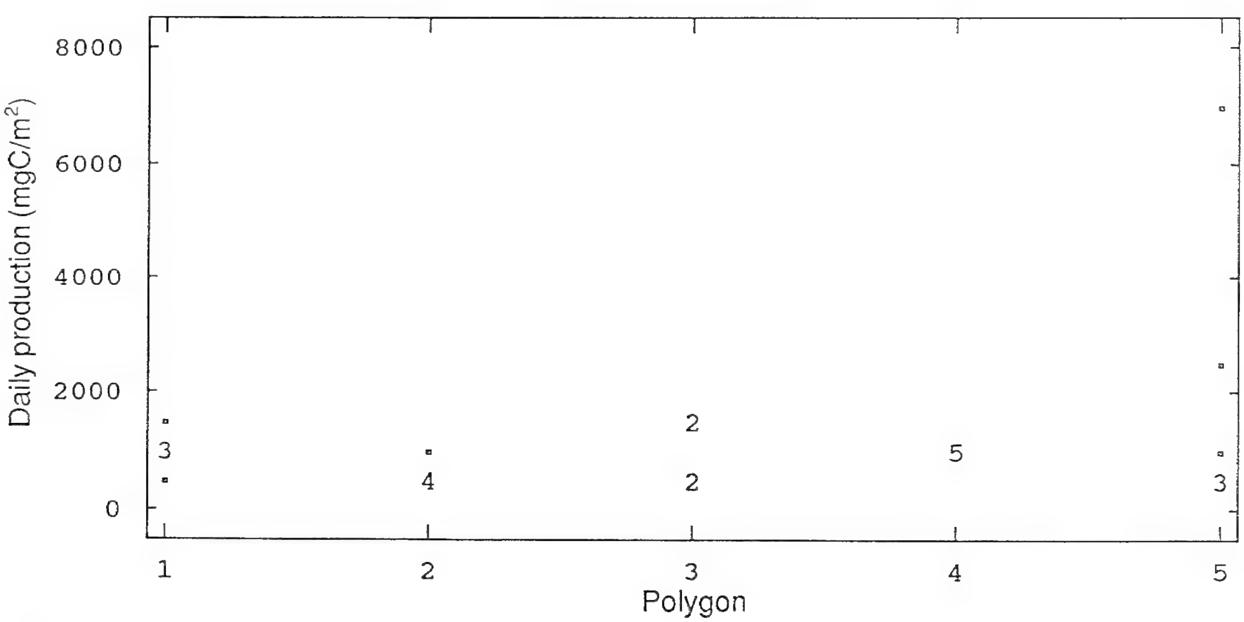


Fig. 1. Hourly and daily productivity rate at each of the four polygons (1-south, 2-east, 3-north, 4-west, (polygon 5 is all the intermediate transect stations). Numbers in the plot represent overlapping data points.

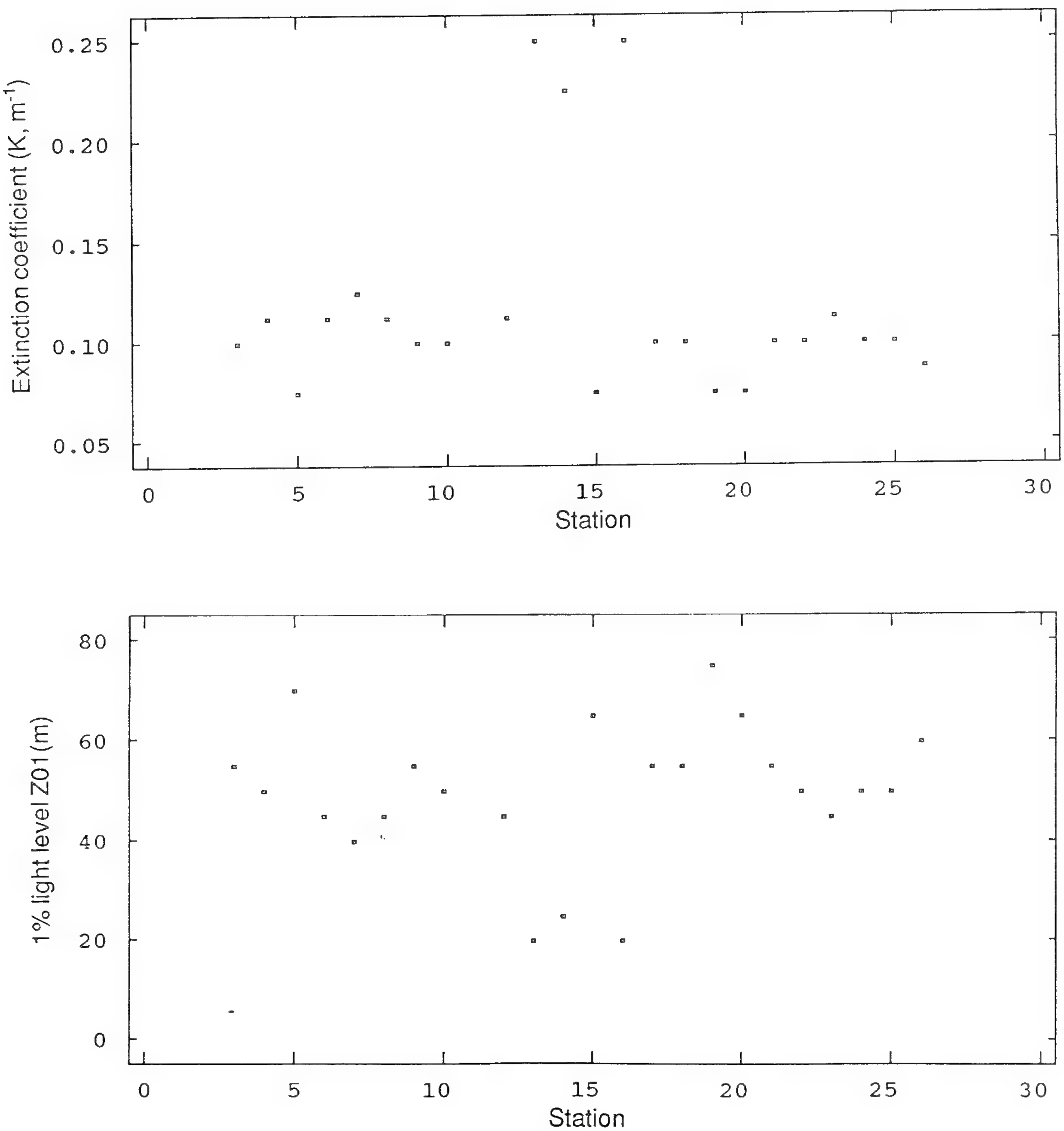


Fig. 2. Extinction coefficient and the depth of the 1% light level plotted for all stations.

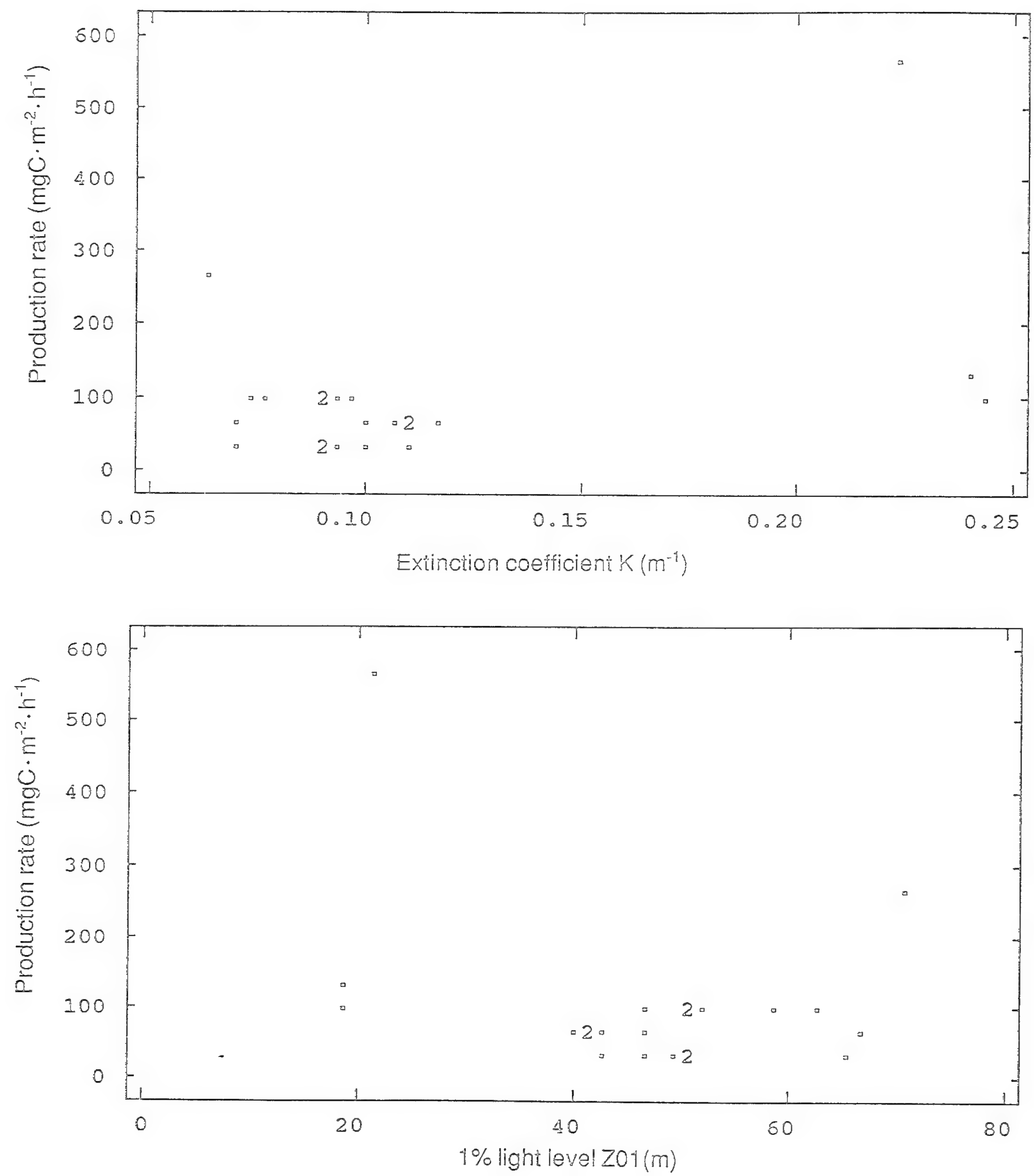


Fig. 3. Hourly areal productivity rates plotted against the extinction coefficient and the depth of the 1% light level.

(stations 13, 14, and 16), and two had extreme values for production (stations 14 and 19). Analysis of variance was unable to detect any differences (at $\alpha=0.05$) among the means of the polygons, when these high stations were removed.

Discussion

The values for production presented here represent summertime conditions in the Bering Sea. It is difficult to extrapolate these values into yearly production rates. However, it is easy to realize that, at least for a short period of time, the production in the region is extremely high. The higher values are similar to those found in temperate estuarine areas (Thayer 1971; Zeeman 1982).

Previous workers report productivity rates of 0.0003 to 4.1 g C m^{-2} d^{-1} for the Bering Sea region (Saino et al. 1979). Koblentz-Mishke et al. (1970) showed primary productivity rates for the Bering Sea ranging from 150 to 500 mg C m^{-2} d^{-1}. Sambrotto et al. (1984) estimated average production, by indirect methods, at 2.7 g C m^{-2} d^{-1} for the Western Bering Strait. Production rates in this study fall within the reported range except the high value of 6.9 g C m^{-2} d^{-1} at station 14. The region around station 14 was unique in that it was characterized as an upwelling area (Whitledge et al., in press).

Lorenzen (1976) states that regions with high production rates (> 0.5 g C m^{-2} d^{-1}), generally have shallower euphotic zones (10-30 m), and a vertically uniform chlorophyll distribution. Areas having low production (<0.5 g C m^{-2} d^{-1}) tend to have euphotic zones >50 m, and a deep chlorophyll maximum. In the present study, 60% of the stations had production rates greater than 0.5 g C m^{-2} d^{-1}. However, only three stations had euphotic zones of 10-30 m (as defined by the 1% light intensity). The chlorophyll distribution was also a poor indicator of primary productivity.

Clearly, what occurs in the Bering Sea is that a significant amount of production is taking place at depth. Figure 4 shows some typical vertical distributions of chlorophyll and productivity. Stations 14 and 25 have a standard surface-productivity maximum and a relatively uniform distribution of chlorophyll. Station 11 has subsurface maxima of both chlorophyll and productivity at about 30 m. An interesting situation is found at station 19, where there is a relatively uniform distribution of chlorophyll, yet there is a large subsurface peak in productivity. This can be explained only by the fact that the population between 30 and 50 m is adapted for photosynthesis at low-light intensities.

Several other stations were found to have high rates of production at depths of 30 m or deeper (Whitledge et al., in press). Much of this deep production was associated with the nutricline. The high nutrient concentrations at these depths combined with good light penetration (10-100 μE m^{-2} s^{-1}) served to provide a fertile ground for phytoplankton growth (Whitledge et al., in press).

The temperatures at the deep production maxima are in the range of -1.5°C to +2°C. Pomeroy and Deibel (1986) suggest that under these conditions, high rates of photosynthesis still may occur, yet microbial degradation is reduced. Such a scenario allows much more of the primary production to be transferred to herbivores and less lost to microbial pathways. This would then be a mechanism which could account for high productivity in the upper trophic levels in the Bering Sea (Washburn and Weller 1986).

During this expedition, high ammonium concentrations were found in the bottom waters between stations 10 and 14. The implication here is that much of the production in the

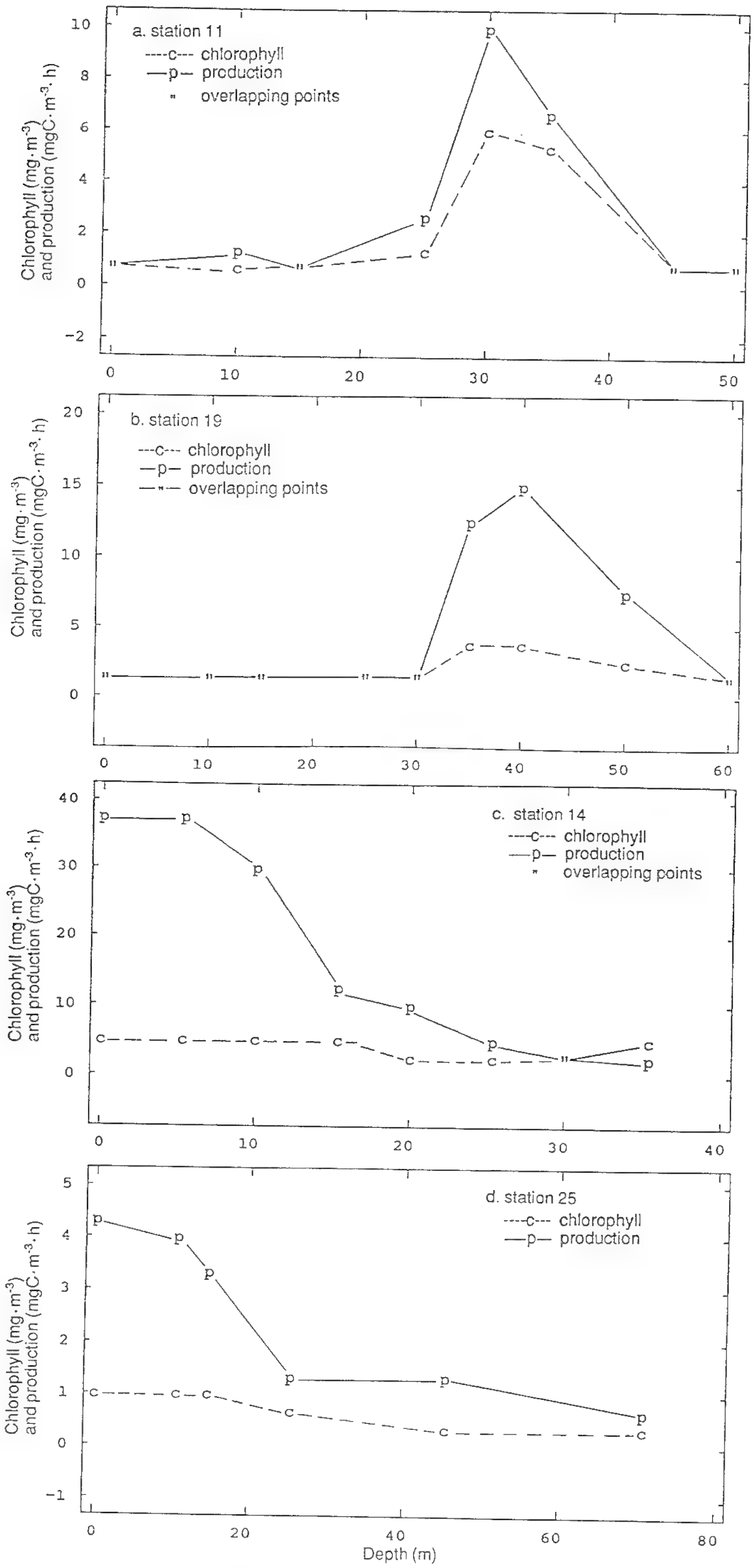


Fig. 4. Productivity rates and chlorophyll concentrations with depth at four selected stations.

water column is finding its way to the sediments, where it is being regenerated. The transfer of large amounts of pelagic organic matter to the sediments would provide a food resource for nekton, epibenthic, and infaunal assemblages. Dredge samples taken during the study corroborated this idea by providing abundant and diverse catches of epibenthic fauna.

High productivity throughout the food chains of the Bering Sea has been attributed to repeated periods of exponential growth of phytoplankton communities throughout the summer (Taniguchi 1969). This is reportedly due to a series of stabilizing and destabilizing events induced by meteorological forcing. We have shown here that other possibilities also exist. The deep productivity maxima and the concomitant higher efficiency of energy transfer to higher trophic levels, while at station 14, there is very high production driven by upwelling. All of these factors provide insights to the abundance of marine life in the Bering Sea.

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PHOTORESPONSES OF PHYTOPLANKTON IN THE BERING SEA

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Introduction

Because the Bering Sea is one of the most productive fishery areas in the world (Hood and Kelly 1974), it is natural to assume that the phytoplankton production might also be great. Indeed, several studies have assessed production and biomass in various areas and found them to be high (Koike et al. 1982; Sambrotto et al. 1984, 1986). To date, little is known of the processes which lead to the rich production in the Bering Sea.

The experiments described here were designed to study the photophysiology of the phytoplankton over a large portion of the Bering Sea. The natural variability of primary production could thereby be established and the physiological state of the phytoplankton with regard to photoadaptation could be described. These studies have several benefits: (1) knowledge of the physiology allows us to develop models of phytoplankton production which could make data gathering much simpler in the future, for example, by applying satellite technology; (2) such models may be used to predict the food potential at lower trophic levels, and ultimately the production of food resources for human populations; and (3) current data on the physiological status of the phytoplankton also provide a baseline for comparison with future data, in order to detect possible influences of the increasing development of resources around the Bering Sea, anthropogenic inputs, and natural perturbations.

The experimental design allowed for a relatively rapid assessment of conditions throughout the Bering Sea basin. The data from specified regions (polygons) may thus be compared with one another and additionally reflect the general summertime conditions for the Bering Sea. The wide scope of the cruise track was inherently one of the best aspects of these experiments in that it allowed us to estimate the variability found throughout the area.

The photophysiology experiments were designed to determine the parameters that mathematically describe the photosynthesis-light relationship for natural populations of phytoplankton. Although numerous functions may describe this relationship, a well-accepted and generally useful model is the hyperbolic tangent function of Jassby and Platt (1976).

Materials and Methods

The cruise track of the RV *Akademik Korolev* proceeded from Dutch Harbor, Alaska, in a somewhat circular fashion around the Bering Sea (frontispiece). Polygons, each comprising five stations, were occupied in four locations. These five stations served as

replicates to characterize the polygon. The polygons were designated north, south, east and west, denoting their relative positions. Additional sampling stations were occupied between the polygons, and one station to the north of the north polygon.

Experiments were conducted at 26 stations on water samples drawn from two depths, one above the thermocline, the other below, and in the chlorophyll peak when appropriate. Sampling depths were determined by examining output from expendable bathythermograph (XBT) casts and submarine light profiles taken with a Li-Cor quantum meter (photosynthetically active radiation, PAR) equipped with a submersible quantum sensor. On-deck light measurements were made with a Li-Cor integrating recording quantum meter throughout the cruise.

Photosynthesis rates were determined at eight light intensities in a shipboard incubator at near sea surface temperatures. Standard ^{14}C and liquid scintillation techniques were used (Strickland and Parsons 1972). All rates were determined in triplicate for each sample at each light intensity and in dark bottles. Light intensities ranged from 1.3 to 750 $\mu E\ m^{-2}\ s^{-1}$ and were generated with high-intensity fluorescent lamps and neutral-density screens. Incubations were done in acid-washed 250 mL polycarbonate flasks, inoculated with 5 μCi $NaH^{14}CO_3$.

Incubations were allowed to proceed for one hour; the samples were then immediately filtered through 0.4 μm Gelman metricel filters. The filters were acidified in scintillation vials with 0.5 mL 1.0 N HCl and later counted in ACS liquid-scintillation cocktail (Amersham).

Primary production rates (mg C $m^{-3}\ h^{-1}$) were calculated and normalized to chlorophyll concentrations (mg Chl/m^3) determined by fluorometric techniques (Strickland and Parsons 1972). The photosynthesis-light (P-I) parameters were determined by fitting the data to a model using nonlinear least-squares regression techniques. Two models were tested, one using the standard hyperbolic tangent function (Jassby and Platt 1976) and another incorporating a photoinhibition parameter (Platt et al. 1980).

$$P = P_{max} \tanh \{\alpha I / P_{max}\} + R$$
$$p = P_s \{1-e^{-a}\}e^{-b} + R$$

where

$$a = \alpha I / P_s$$
$$b = \beta I / P_s$$

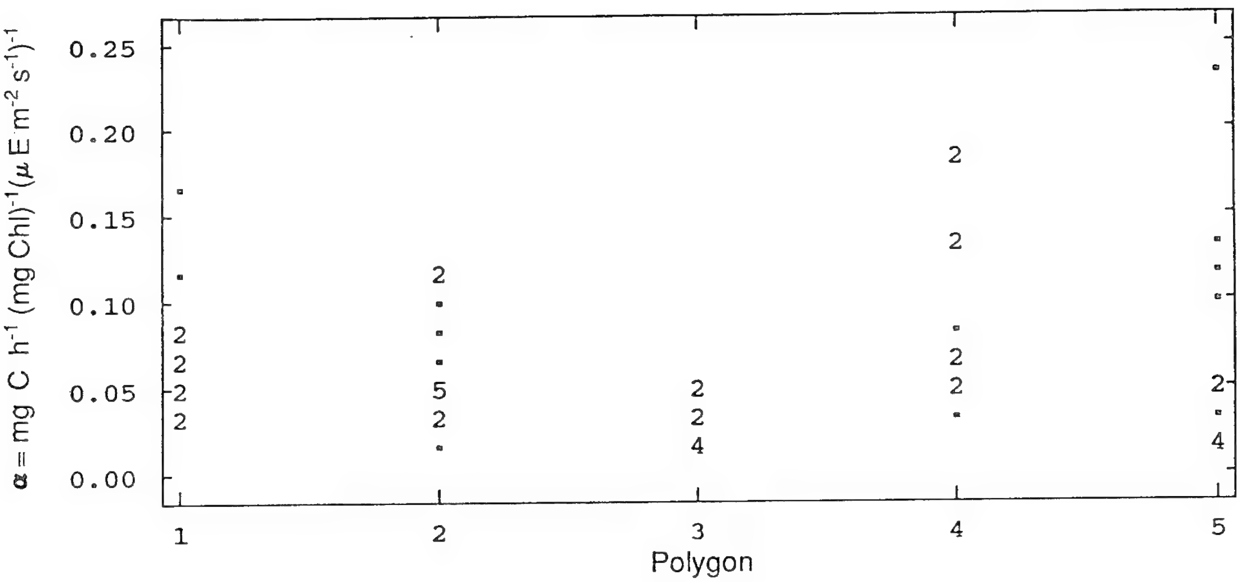
In the equations, P_{max} and P_s are the maximum photosynthetic rate, (mg C h^{-1}[mg Chl]$^{-1}$), α is the initial slope (mg C h^{-1}[mg Chl]$^{-1}$ [$\mu E\ m^{-2}\ s^{-1}$]$^{-1}$), β is the photoinhibition parameter, (mg C h^{-1}[mg Chl]$^{-1}$ [$\mu E\ m^{-2}\ s^{-1}$]$^{-1}$), I is the light intensity, ($\mu E\ m^{-2}\ s^{-1}$), and R is the intercept, (mg C h^{-1}[mg Chl]$^{-1}$) at zero light. The best-fit model was chosen for each set of data by comparison of the sum of squares.

The experimental design did not allow for the examination of diurnal variability in the P-I parameters. The existence of such fluctuations are known in other populations (Harding et al. 1982). The determination of diurnal variations, and their potential effects on the estimation of productivity are left to future investigations.

Statistical analyses were performed using BMDP (Dixon 1975) on a Prime minicomputer or with SYSTAT (Wilkinson 1986) on an IBM AT clone.

Results

The data gathered from the P-I experiments are summarized in Fig. 1. They are arranged by polygon number, with those stations along transects being grouped in polygon 5. The overall means and standard deviation of α, P_{max}, the intercept, and the β coefficient are 0.06 ± 0.05, 4.17 ± 3.3, -0.109 ± .18, and 0.003 ± 0.003, respectively. The frequency distribution of α and P_{max} values are shown in Fig. 2.



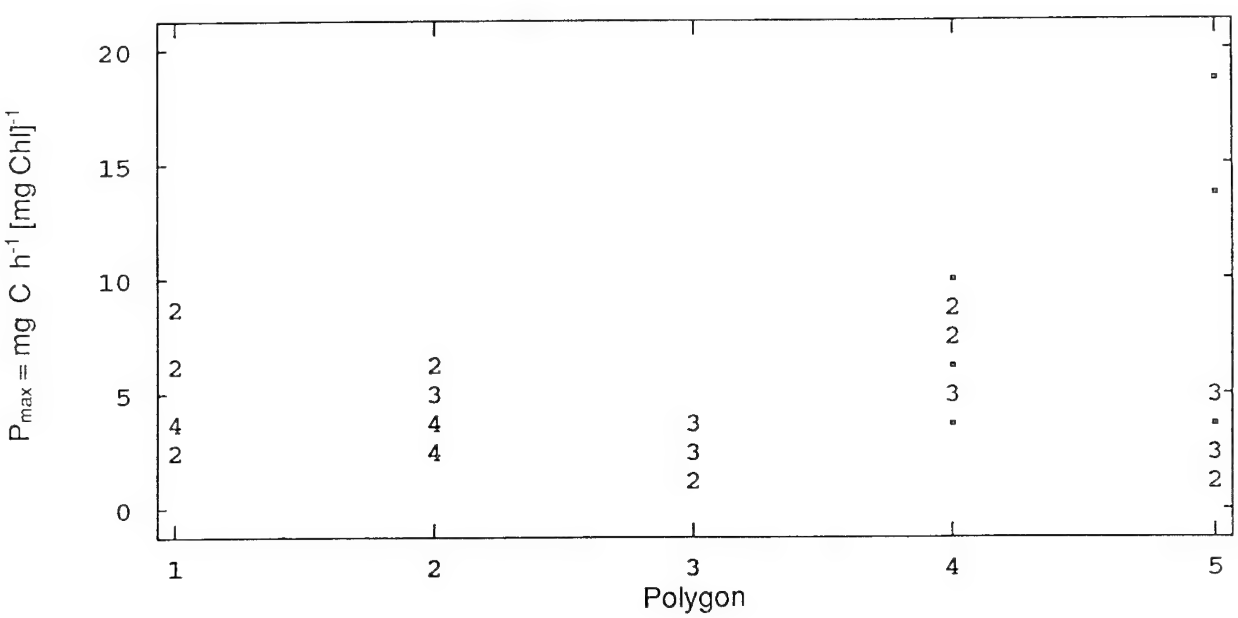


Fig. 1. Experimental results showing α, P_{max}, Intercept, and β for each polygon. Polygon 5 is composed of all the intermediate transect stations not within the four major polygons. Numbers signify overlapping data points.

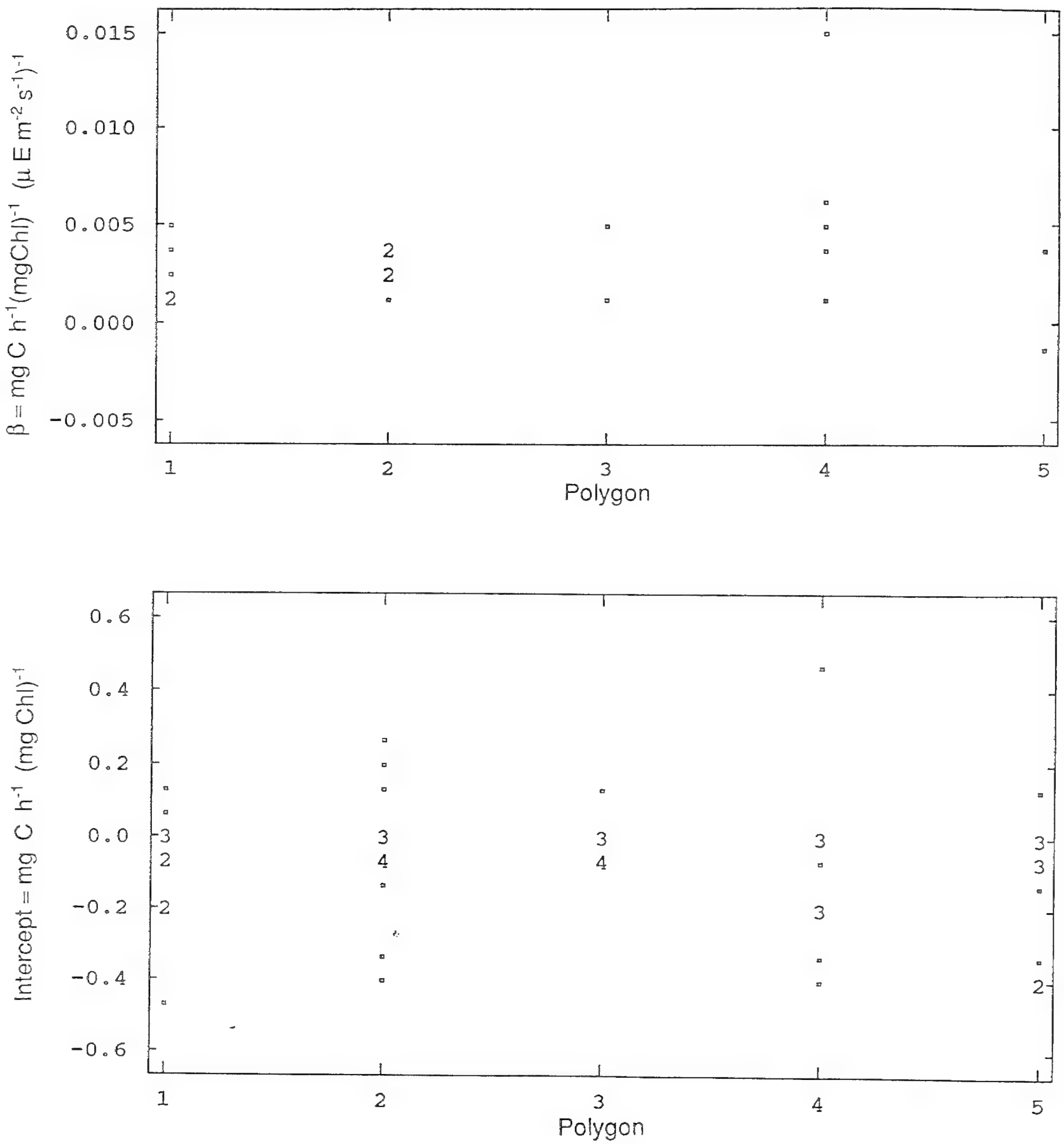


Fig. 1. Continued.

The data are clearly heteroscedastic and Bartlett's test shows the variances to be non-uniform. This limits comparative analysis to some extent. Transformations were made of the raw data prior to further statistical analysis. The arcsine transformation was used for α, the intercept (R), and β. P_{max} was transformed by taking the square root. Probability plots of the transformed data produced straight lines. In addition, quantile plots were distinctly sigmoid. Both of these types of plots indicated that the data after transformation were normally distributed.

Analysis of variance (ANOVA) was used to test for differences between means among the polygons. Because the polygon 5 was not a specific locality, it was excluded from this particular analysis. Results showed that differences were present for α ($P=.001$) and P_{max} ($P<.001$), while intercept and β were not significantly different between polygons. Duncan multiple range tests ($\alpha=0.05$) showed that only the north polygon was different from the other three polygons. Values of α and P_{max} were generally lower in this region than anywhere else in the Bering Sea.

Data plotted by station in Fig. 3 illustrate the fact that certain unusual features were associated with the nonpolygon stations. For example, station 14 has relatively high α and P_{max} values.

VARIABLE ALPHA , N = 52

VALUE	COUNT	PERCENT
0.000	10	19.23
0.020	12	23.08
0.040	13	25.00
0.060	4	7.69
0.080	2	3.85
0.100	5	9.62
0.120	2	3.85
0.140	0	.00
0.160	2	3.85
0.180	1	1.92
0.200	0	.00
0.220	1	1.92

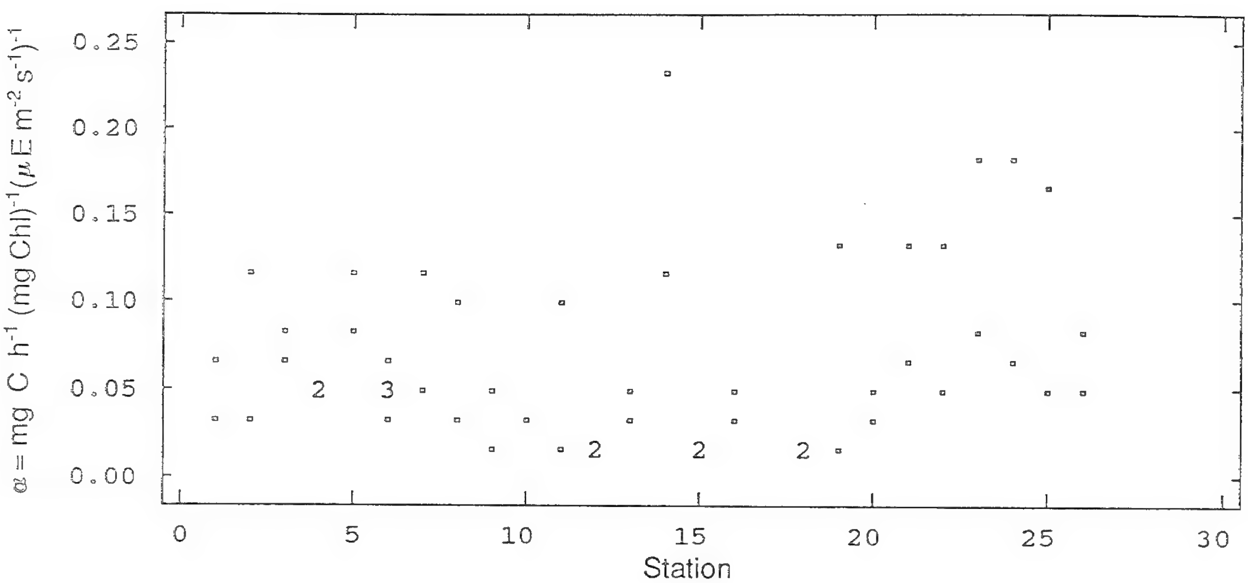
VARIABLE PMAX , N = 52

VALUE	COUNT	PERCENT
0.000	12	23.08
2.000	18	34.62
4.000	13	25.00
6.000	2	3.85
8.000	5	9.62
10.000	0	.00
12.000	1	1.92
14.000	0	.00
16.000	0	.00
18.000	1	1.92

Fig. 2. Histograms of α and P_{max} values.

Discussion

Most values of the P-I parameters were close together, as can be seen from the histograms in Fig. 2. The exception seemed to be station 14, which had, by far, the highest α and P_{max} values, although the intercept and β values were in line with those at the other stations (Fig. 3). The data from the Bering Sea are similar to those from other studies, although the high values seem to be higher than most (Table 1). The extreme values at station 14 were in an area of upwelling. Surface water had temperatures of less than 0°C and elevated nutrient levels (Whitledge et al., in press; the high values recorded here are indicative of the general health of the phytoplankton). Phytoplankton are well supplied with light and nutrients and are probably functioning at the peak of their capacity. Despite the low temperatures, the algae in this study were exhibiting very high photosynthetic rates.



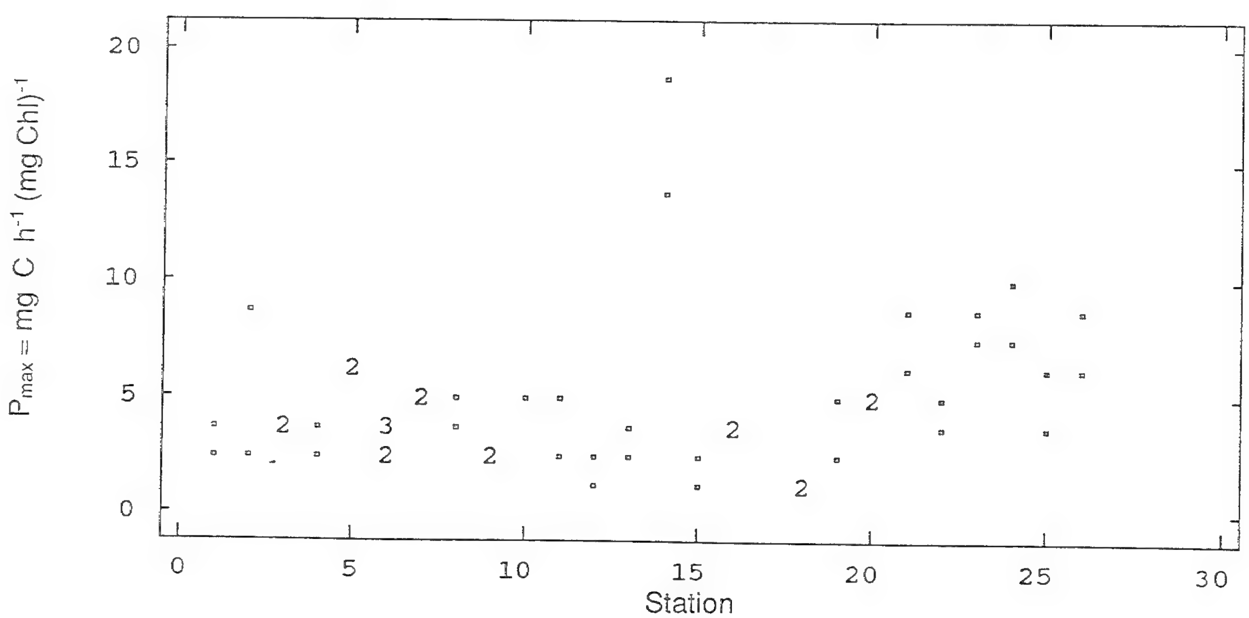


Fig. 3. Presentation of α, P_{max}, Intercept, and β for all stations.

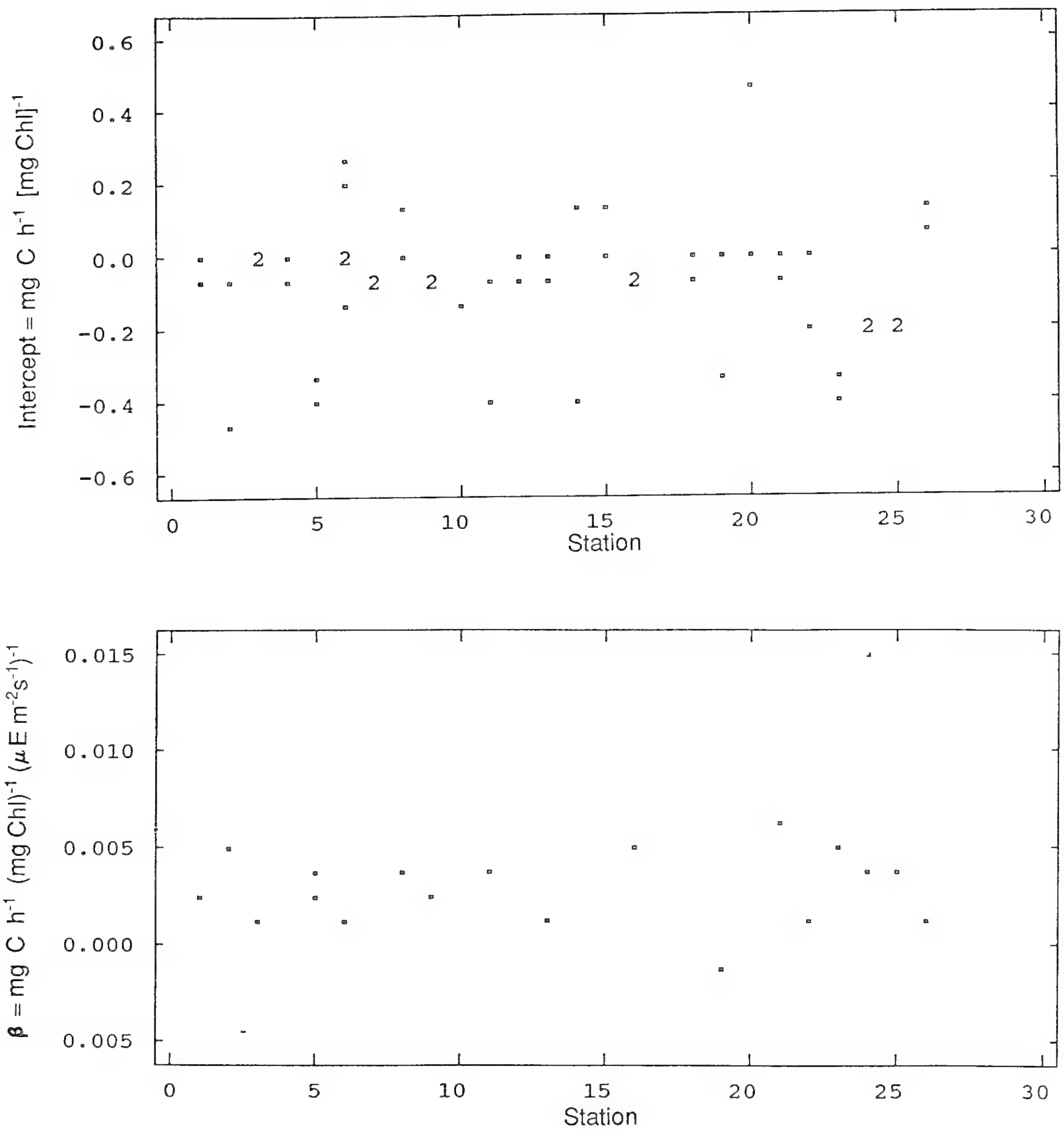


Fig. 3. Continued.

Table 1. *Comparative values of photosynthetic parameters.*

Alpha[a]	P_{max}[b]	Location	Reference
0.012-0.154	0.7-5.0	St. Margaret's Bay Nova Scotia	Platt & Jassby 1976
0.013-0.056	1.8-5.4	Celtic Sea Size fractionated	Joint 1986
0.008-0.038	1.8-3.4	Porcupine Seabight Size fractionated	Joint 1986
0.004-0.091		Cultures	Parsons et al. 1977
0.007-0.112		Natural populations	Parsons et al. 1977
	1.0-1.5	Arctic	Steeman-Nielsen and Hanson 1959
	0.8-5.0	Bering Sea	Motoda and Kawamura 1963
	1.5-4.5	Chuckchi Sea	Hameedi 1978
0.001-0.231	0.8-18	Bering Sea	This report

[a]α = (mg C h^{-1}[mg Chl]$^{-1}$ [μE m^{-2} s^{-1}]$^{-1}$)
[b]P_{max} = (mg C h^{-1}[mg Chl]$^{-1}$)

Photoinhibition was detected in 19 out of 52 experiments as is shown by the number of β values in Fig. 3. This indicates that less than half of the phytoplankton populations measured were low-light adapted. The number of experiments during which photoinhibition was detected was five each in the south, east, and west polygons, while only two instances each were found in the north polygon and at the intermediate transect stations (polygon 5).

Photoinhibition was more prevalent for samples from lower in the water column than for surface waters, as might be expected. Only at stations 5 and 16 was inhibition detected for surface-dwelling populations. For the rest of the experiments, a lack of photoinhibition probably meant that the light history of the phytoplankton had included recent exposure to high-light intensities. Time scales for photoadaptation may vary from minutes to days (Jones 1978; Platt and Gallegos 1980; Prezelin and Matlick 1980). The most probable reason for high light adaptation is turbulent mixing of the algae into the near-surface waters where intensities may reach 1200 μE m^{-2} s^{-1}. Turbulent mixing in deep waters may be induced by meteorological forcing or current shears. In shallow waters there is also mixing due to bottom friction in relation to tidal currents.

The fact that fewer instances of photoinhibition were found at the northern stations is perhaps indicative of higher mixing rates in this area. It may also be due to prolonged periods of clear weather in this area, compared to the cloudier southern stations, which were in the path of storm tracks. Storms generally mean greater turbulence, and thus should provide more opportunity for the phytoplankton to be circulated to the near-surface waters. The increased mixing could be counteracted by

the reduced light intensities beneath cloud cover and thereby maintain the phytoplankton in a state of low-light adaptation.

The experiments here have shown that the Bering Sea has phytoplankton P-I responses similar to those in other parts of the oceans. The exceptionally high values of some parameters are apparently associated with upwelling regions. This study and previous work show that the Bering Sea as a whole can in fact support a tremendous fishery. The high values of the P-I parameters in some areas are a clue to the ability of the Bering Sea to maintain this fishery.

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PIGMENT COMPOSITION AND PHYTOPLANKTON BIOMASS

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Introduction

The Bering Sea is a productive high-latitude oceanic environment whose shelf supports large standing stocks of zooplankton and marine vertebrates. In contrast to most oceanic regions, the Bering Sea has high levels of phytoplankton biomass and production associated with waters overlying its shelf domain, as well as its open-ocean domain (Holmes 1958; Kawarada 1963; Taniguchi 1969; McRoy et al. 1972; Koike et al. 1982; Sambrotto et al. 1984, 1986). Walsh et al. (1985) proposed that a significant proportion of the shelfbased production is transported to the Bering Sea slope, which serves as a major storage site for atmospheric carbon dioxide. The fact that the zooplankton-to-phytoplankton biomass ratio calculated for the Bering Sea is higher than most oceanic areas (Motoda and Minoda 1974) suggests that there is an efficient transfer of phytoplankton carbon to higher trophic levels.

Sambrotto et al. (1986) have shown that there is a significant degree of seasonal variability in both phytoplankton biomass and production of the southeastern Bering Sea shelf. The shallowing of the mixed layer is the most important process responsible for bloom initiation, which occurs annually during early May. The investigators also concluded that vertical mixing forced by atmospheric events is important in controlling the magnitude of spring bloom. Interannual variations in zooplankton biomass have also been documented for the Bering Sea, possibly reflecting variations in meteorological conditions (Motoda and Minoda 1974).

During early summer and midsummer, boreal-oceanic diatoms dominate the phytoplankton community of the open western and central Bering Sea and the eastern Bering Sea shelf, while temperate-neritic diatoms are characteristically found in the vicinity of the Aleutian Island chain (Motoda and Minoda 1974). The dominant offshore diatoms include representatives from the following genera: *Chaetoceros* sp., *Rhizosolenia* sp., *Denticula* sp., *Thalassiosira* sp., *Nitzschia* sp., and *Fragilaria* sp. On the southeastern Bering Sea shelf, diatoms are dominated by *Thalassiosira aestivalis* and *T. nordenskioldii* during prebloom conditions (April) and *Chaetoceros* spp. (especially *C. debilis*) during bloom conditions which occur during May (Sambrotto et al. 1986). Kisselev (1937) also reported the presence of dinoflagellates and green algae in the northern Bering Sea.

To better understand the distributions of the major algal groups and the physico-chemical factors that influence them, algal pigments were measured by high-performance liquid chromatography (HPLC) at series of stations occupied in the Bering Sea. Algal pigments and their degradation products are shown to be useful as chemotaxonomic markers for mapping phytoplankton distributions and zooplankton grazing activity. The dominant algal pigments are examined in relation to the chemical, optical, and physical properties of the water column to provide insight into the factors

influencing phytoplankton summer biomass distributions in the Bering Sea.

Methods

A series of four polygon (5 stations in the form of a box) sampling sites located in the southern, eastern, northern, and western regions of the Bering Sea were occupied during July 1984 by the RV *Akademik Korolev* (frontispiece). Water samples were collected at stations 2-25 for the determination of photosynthetic pigments and their degradation products. One-liter water samples were filtered through 0.4-μm polyester Nuclepore filters, frozen at dry ice temperatures and transported to Texas A&M University for HPLC pigment analysis. Upon arrival at the laboratory, the samples were transfered to a liquid-nitrogen storage container and analyzed for pigment content over a 6-month period. Chlorophyll *a* was found to be stable for at least eighteen months under these conditions ($[\text{Chl } a]_{t=18\text{ mo.}}/[\text{Chl } a]_{t=0\text{ mo.}} = 1.02 \pm 0.12$; n=5). Previously described HPLC methodology (Bidigare et al. 1985) has been modified to provide separations of the major carotenoid accessory pigments. In the laboratory, filters were extracted in 2 mL of 90% acetone for 24-48 hours (in the dark at -10°C) and centrifuged for 5 min to remove cellular debris.

Chlorophyll and carotenoid pigments were separated using a SpectraPhysics Model SP8100 liquid chromatograph and Radial-Pak C18 column at a flow rate of 10 mL/min. Samples were prepared for injection by using the ion-pairing agent described by Mantoura and Llewellyn (1983). A two-step solvent program was used to separate the various phytoplankton pigments associated with the marine suspended-particulate samples. After injection (500-μL sample), mobile phase A (80:10:10; methanol:water:ion-pairing agent) was ramped to mobile phase B (methanol) over a 12-min period. Mobile phase B was then pumped for 10 min for a total analysis time of 22 min. Chlorophyll/carotenoid and phaeopigment peaks were detected with a Waters Model 440 Fixed Wavelength Detector (436 nm) and a Perkin-Elmer Model 650-40 spectrofluorometer (Ex=434 nm; Em =670 nm), respectively. Representative absorbance and fluorescence chromatograms are shown in Fig. 1. Peaks were quantified by peak area. The specific algal pigments measured include chlorophylls *a*, *b*, and *c*; chlorophyllide *a*; phaeophorbide *a*; phaeophytin *a*; peridinin; fucoxanthin; diadinoxanthin; lutein plus zeaxanthin; and carotene. Calibration standards were obtained from Sigma Chemical Co. (chlorophylls *a* and *b* and β-carotene) or purified by two-dimensional thin-layer chromatography (Jeffrey 1981). Concentrations of the pigment standards were determined spectrophotometrically (Jeffrey 1972; Jeffrey and Humphrey 1975; Mantoura and Llewellyn 1983; Bidigare et al. 1985). The HPLC method employed is not capable of separating lutein from zeaxanthin.

Pigment biomass (μg/m^2) at each station was calculated by integrating the major algal pigment concentrations (chlorophyll *a*, fucoxanthin, chlorophyll *b*, and peridinin) with respect to depth. Integration was performed for the upper 70 m (or less, depending on bottom depth).

Results

The quantitatively important algal pigments measured in the suspended particulate samples (n = 220 samples) collected during this study were chlorophylls *a*, *b*, and *c*; fucoxanthin; diadinoxanthin; lutein plus zeaxanthin; peridinin; and carotene. Integrated chlorophyll *a* biomass for the 25 stations sampled are presented in Table 1. Chlorophyll biomass varied by an order of magnitude depending on station location, with values ranging from 10.7 (station 8) to 137.4 mg chl *a*/m^2 (station 13). For illustration's sake, distributions of integrated chlorophyll *a* biomass have been contoured (despite the limited data set) for the Bering Sea in July 1984 (Fig. 2). Highest chlorophyll *a* levels were located on the northern Bering

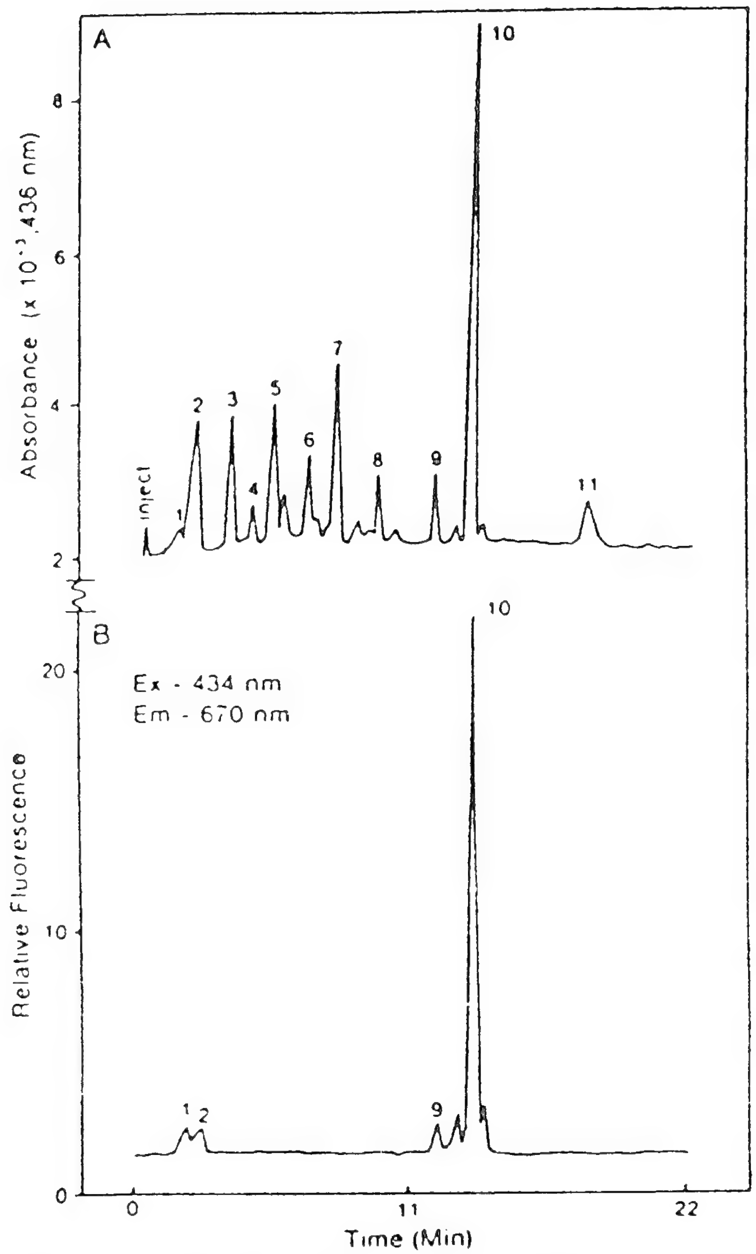

Fig. 1. Reverse-phase HPLC absorbance and fluorescence chromatograms for a mixture of plant pigments. Peak identities are (1) chlorophyllide *a*; (2) chlorophyll *c*; (3) peridinin; (4) dinoxanthin; (5) fucoxanthin; (6) violaxanthin; (7) diadinoxanthin; (8) lutein (plus zeaxanthin); (9) chlorophyll *b*; (10) chlorophyll *a*; (11) crotene.

Table 1. *Integrated pigment concentrations (μg pigment/m²) for all stations sampled in the Bering Sea during July 1984.*

Station No.	Chlorophyll *a*	Fucoxanthin	Chlorophyll *b*	Peridinin
2	19,310	10,360	2,633	193
3	34,540	20,788	4,458	428
4	39,575	21,058	3,355	383
5	12,425	3,750	3,863	193
6	20,458	7,673	4,808	175
7	11,468	4,635	2,163	140
8	10,733	2,265	3,563	145
9	19,070	7,003	3,810	85
10	15,183	10,013	2,300	30
11	62,518	41,528	2,035	38
12	45,140	48,915	1,973	0
13	137,375	86,588	1,555	0
14	60,923	43,598	353	0
15	28,750	19,120	273	30
16	109,685	83,343	518	100
17	37,585	27,768	608	45
18	34,960	29,333	330	0
19	24,118	17,248	548	30
20	14,863	8,710	1,143	220
21	12,160	4,925	1,973	190
22	23,865	9,458	4,718	205
23	13,530	3,445	3,290	380
24	13,595	4,765	2,113	138
25	19,593	9,158	2,858	200
26	18,883	7,898	3,020	365

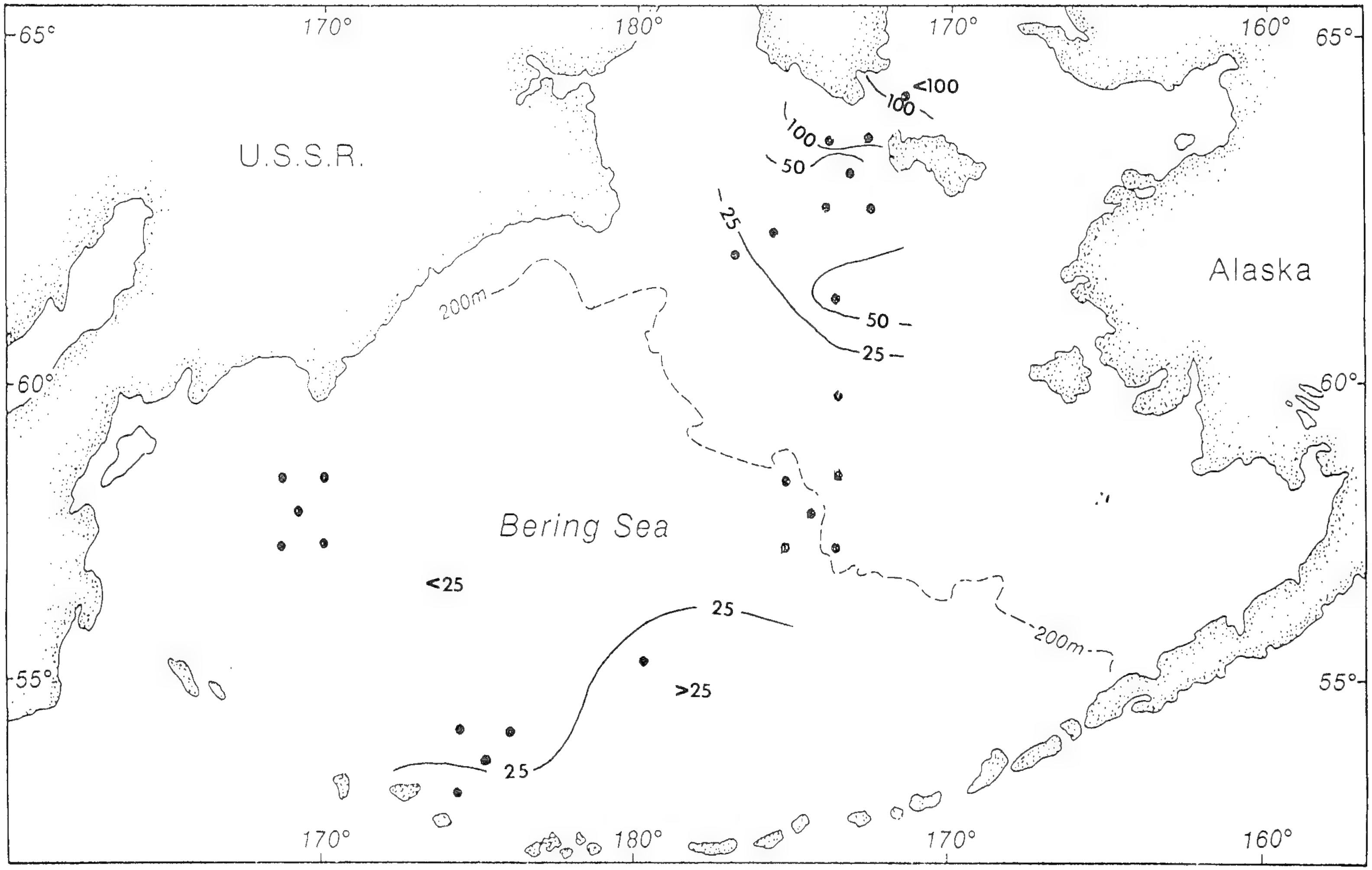

Fig. 2. Contours of integrated chlorophyll *a* biomass (mg/m^2) for stations 2-26, July 1984.

shelf and in the Anadyr Strait (>50 mg chl a/m^2). By comparison, lowest chlorophyll *a* levels were measured for the western Bering Sea (i.e., west of the shelf-slope break), where values were <25 mg chl a/m^2. These chlorophyll *a* biomass values are consistent with measurements made during summertime (post-bloom) on the southeastern Bering shelf (Sambrotto et al. 1986). Considerably higher values have been reported for the Bering Strait, where chlorophyll *a* biomass levels exceed 200 mg/m^2 (Sambrotto et al. 1984).

Table 1 also includes integrated concentrations of fucoxanthin, chlorophyll *a*, and peridinin for all stations occupied during the cruise. Integrated fucoxanthin concentrations were highest at stations 11-14 and 16, with values in excess of 40 mg/m^2. Maximum chlorophyll *b* levels (>4 mg/m^2) were measured at stations 3, 6, and 22 located in the south, west, and east polygons, respectively. Integrated peridinin concentrations, in comparison, were two orders of magnitude lower than chlorophyll *a*, with a maximum value of only 0.4 mg/m^2 (stations 3, 4, 23, and 26).

Distributions of chlorophylls *a* and *b*, peridinin, and fucoxanthin along the transect line between the Aleutian Islands and the Anadyr Strait are shown in Fig. 3. Chlorophyll *a* concentrations ranged from 10 to 5,000 ng/L (stations 12, 16, and 18). Chlorophyll *a* maxima (>500 ng/L) were also measured at stations 3, 4, 6, 9, and 25. Concentrations of fucoxanthin, chlorophyll *b*, and peridinin were locally elevated over the shelf, at the shelf-slope break, and just north of the Aleutian Islands, respectively.

The quantitatively important chlorophyll *a* degradation products measured were chlorophyllide *a* and phaeophorbide *a* (Fig. 4); concentrations of phaeophytin *a* were either low or below the limit of HPLC quantification. Chlorophyllide *a* concentrations (data not shown) reached elevated levels (>1500 ng/L) at station 12 and probably reflect the presence of chlorophyllase-containing diatoms. Phaeophorbide *a* concentrations were highest just beneath the pycnocline, suggesting that water column processes are important in organic matter consumption.

Discussion

The concentrations of photosynthetic pigments in the marine environment are primarily dependent on the quantity, species composition, and photoadaptative state of the phytoplankton present. For these reasons, accessory chlorophyll and carotenoid pigments have been used as diagnostic "tags" for investigating algal distributions and their physiological processes. In coastal waters off Australia, Jeffrey (1974) documented the usefulness of accessory pigments for examining phytoplankton distributions in the water column. The thin-layer chromatographic method employed identified the major pigments as chlorophylls *a,b,* and and *c*; carotene; astaxanthin; fucoxanthin; peridinin; diadinoxanthin; and neoxanthin. Chromatographic data were used to "fingerprint" vertical and temporal variations in the phytoplankton community structure.

Several recent investigations have demonstrated the utility of HPLC as a "chemotaxonomical" tool for identifying marine algal groups. For example, high concentrations of zeaxanthin were used to infer the presence of cyanobacteria in the North Sea and tropical Atlantic Ocean (Gieskes and Kraay 1983a). In another study, the dominance of a symbiotic cryptomonad was established for a spring bloom in the central North Sea by HPLC identification of alloxanthin, a carotenoid characteristic of this marine algal group (Gieskes and Kraay 1983b). HPLC pigment analysis has also been shown to be useful for characterizing phytoplankton biomass and compositional changes across frontal systems located at the northern

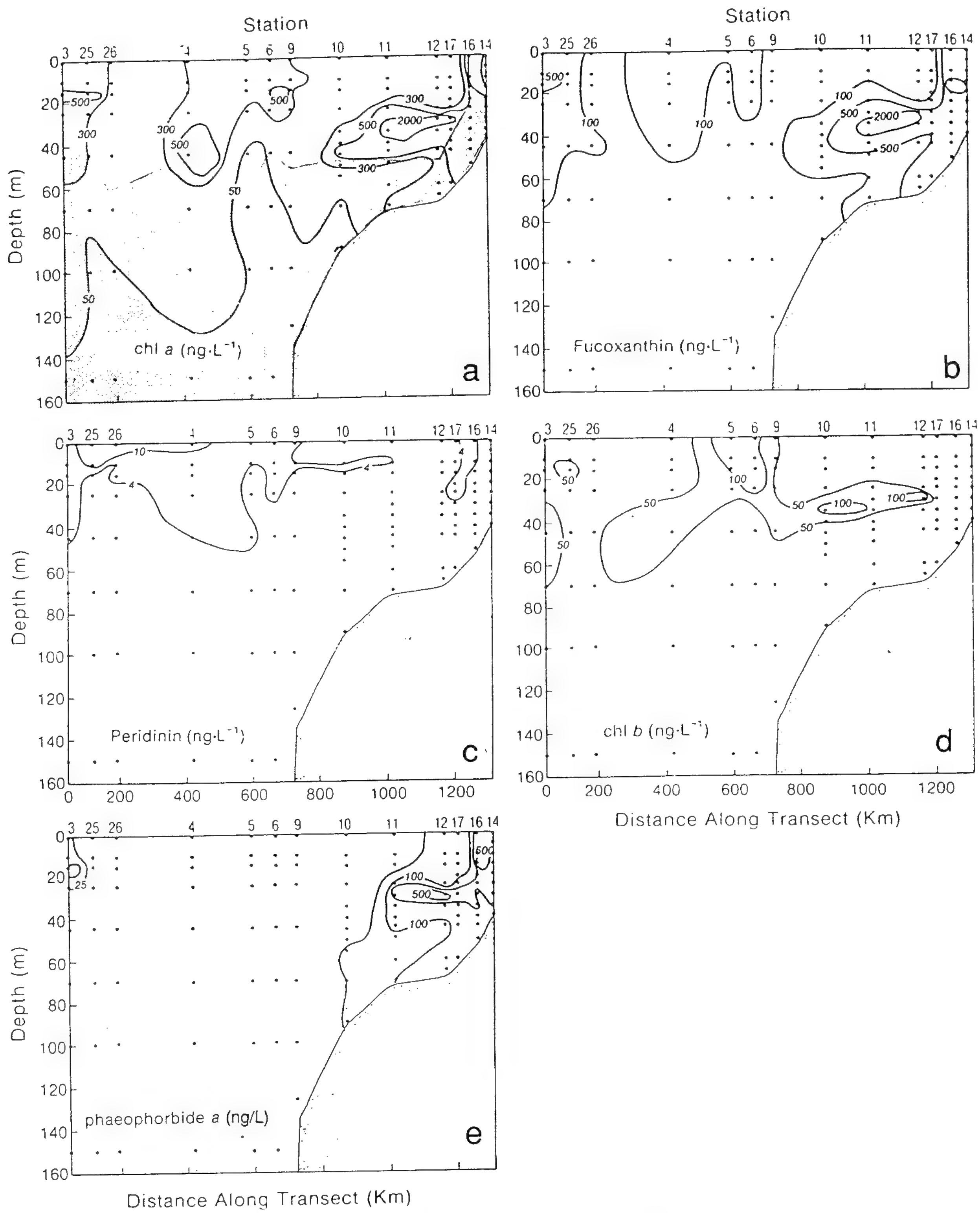

Fig. 3. Vertical distributions of chlorophyll *a*; fucoxanthin; peridinin; chlorophyll *b*; and phaeophorbide *a* along the transect between the Aleutian Islands and the Anadyr Strait. The hatched area shown in panel a marks the depths of the 1% light level along the transect.

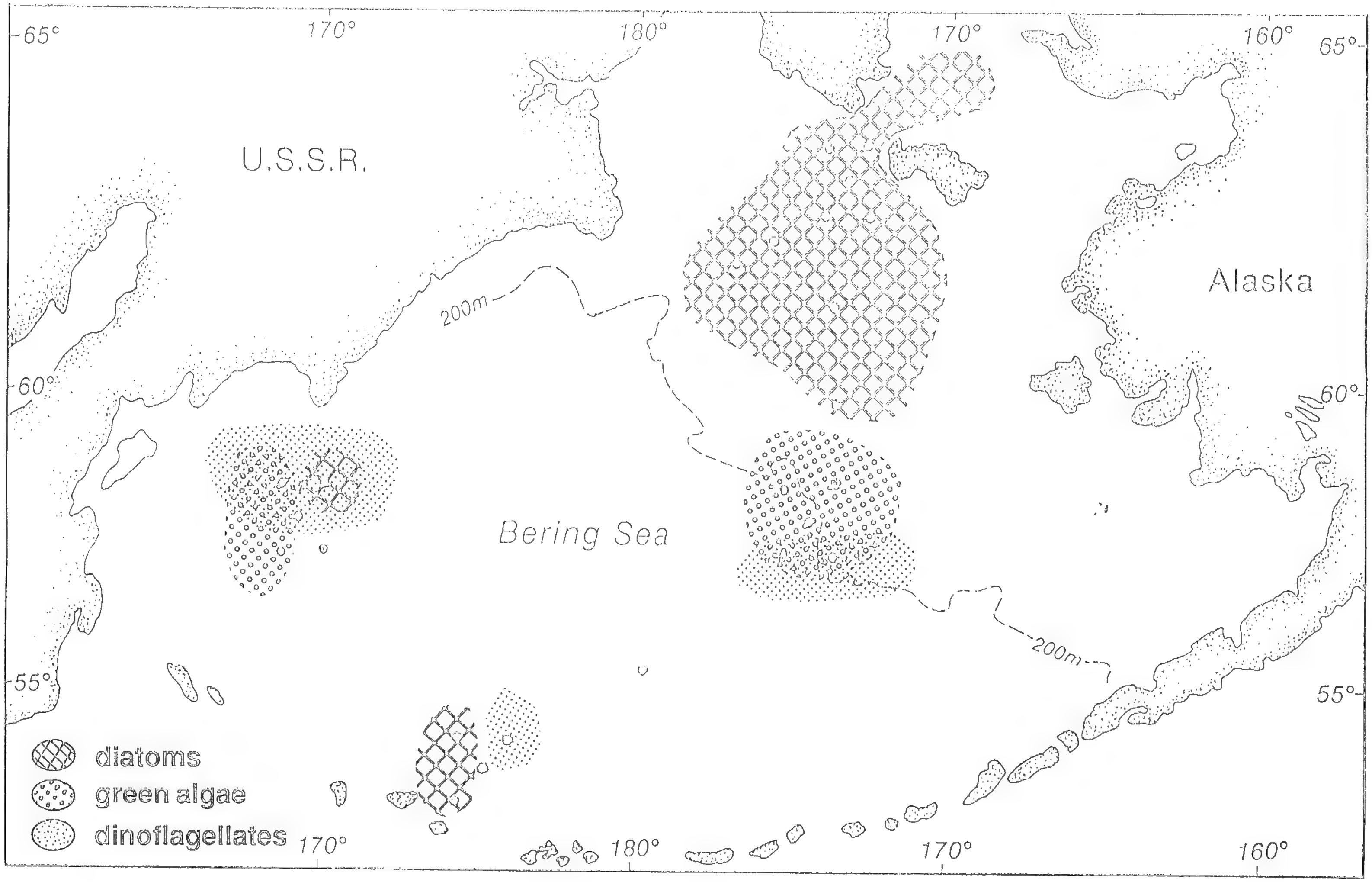

Fig. 4. Distribution of the major algal groups in the Bering Sea during July 1984.

wall of the Gulf Stream (Arnone et al. 1986; Trees et al. 1986) and in the Santa Barbara Channel (Smith et al. 1987). A summary of the important phytoplankton pigments and degradation products and their taxonomic and physiological significance is given in Table 2.

Total chlorophyll *a* biomass was partitioned into contributions by diatoms, green algae, dinoflagellates, and "other" phytoplankton by applying published accessory pigment-to-chlorophyll *a* ratios (Prezelin 1976; Abaychi and Riley 1979; Hooks et al. 1987) to the integrated

Table 2. *Important phytoplankton pigments used as diagnostic "tags" and their taxonomic/ physiological significance.*

Pigment	Significance	Reference
Chlorophyll *a*	Phytoplankton biomass	Jeffrey (1980)
Chlorophyllide *a*	Chlorophyllase-containing diatoms	Jeffrey (1974)
Chlorophyll *a*	Green algae	Jeffrey (1974)
Chlorophyll *c* Fucoxanthin	Diatoms and/or Chrysophytes	Jeffrey (1980)
Peridinin	Dinoflagellates	Jeffrey (1974)
Butanoyl-fucoxanthin	Chrysophytes	Liaaen-Jensen (1985)
Hexanoyl-fucoxanthin	Prymnesiophytes *Emiliania huxleyi* *Gyrodinium aureolum*	Gieskes and Kraay (1986) Norgard et al. (1974) Tangen and Bjornland (1981)
Prasinoxanthin	Prasinophytes	Foss et al. (1984)
Zeaxanthin	Cyanobacteria	Guillard et al. (1985)
Alloxanthin	Cryptophytes	Gieskes and Kraay (1983b)
Zeaxanthin α,β-carotene Diadinoxanthin(?)	Photoprotectants	Paerl et al. (1983) Paerl et al. (1983) Jeffrey (1980)
Phaeophorbide *a*	Zooplankton grazing	Jeffrey (1974)

concentrations of fucoxanthin, chlorophyll *a*, and peridinin, respectively, given in Table 1. Biomass contributions by "other" phytoplankton (prymnesiophytes, chrysophytes, cryptophytes, and/or cyanobacteria) were calculated by difference as follows:

$$[\text{Chl } a]_{\text{other}} = [\text{Chl } a]_{\text{total}} - [\text{Chl } a]_{\text{diat}} - [\text{Chl } a]_{\text{green}} - [\text{Chl } a]_{\text{dinofl}}$$

These calculations should be considered as a first-order approximation, because the ratios of accessory pigments to chlorophyll *a* are not constants and will vary with the photo-adaptative state of the resident phytoplankton (e.g., Prezelin 1976). However, these data do provide insight to the distributions of the major algal groups at the "Class" level. In considering all the stations sampled, the calculations suggest that more than half of the chlorophyll *a* biomass (52%-100%) could be accounted for by the diatoms, green algae, and dinoflagellates (Table 3). The contributions by "other" phytoplankton ranged from 0% to 48% and were most significant at selected stations in the eastern (stations 6-9), western (stations 21-24), and southern (stations 25-26) polygons. Diatoms, as inferred from the distributions of fucoxanthin, were by far the most abundant algal group and accounted for 20%-100% of the total chlorophyll *a* biomass, with highest contributions on the northern Bering Sea shelf. Green algae, as inferred from the presence of chlorophyll *a*, were most abundant at stations 5-9 and 22-23. The largest contribution was calculated for station 8, where green algae comprised 39% of the total chlorophyll *a* biomass. Dinoflagellates, in comparison, were a minor biomass component and accounted only for a maximum of 3% of the total chlorophyll *a* biomass at station 23 located in the western Bering Sea.

In applying the chemotaxonomic information discussed above, it is obvious that phytoplankton were distributed as overlapping zones along the main transect. The pigment sections show that phytoplankton biomass dramatically increased over the Bering Sea shelf (stations 10-12; Fig. 3A) and that this community was primarily dominated by diatoms (Fig. 3B). The chlorophyll *a* maxima at these stations were coincident with the depth of the nitracline. Highest primary production rates and dissolved oxygen levels were also measured at these stations. The depth of the euphotic zone (as defined by the 1% light level) was fairly constant along the southern portion of the transect (stations 3-12), with values ranging from 40 to 60 m (Fig. 3A). At the northernmost stations, the euphotic zone shallowed to 20 m. The chlorophyll *a* maxima at most stations were located just above the depth of the 1% light level. At station 14, however, the highest chlorophyll *a* concentrations were found below the depth of the euphotic zone (20-40 m), suggesting that vertical mixing was important in controlling phytoplankton distributions at this station. These data may partially explain the anomalous P-I parameters determined for phytoplankton sampled at station 14. The fucoxanthin-to-chlorophyll *a* ratios calculated for this station (see below) showed a weak depth-dependent increase (about 10%), suggesting that the phytoplankton were well mixed in the water column.

Most of the zooplankton grazing, as evidenced by elevated phaeophorbide *a* levels (Table 2; Fig. 4), was also localized on the northern Bering Sea shelf. This conclusion is substantiated by the fact that the highest mesozooplankton biomass was also measured in this region of the Bering Sea during July 1984.

Chlorophyll *a* concentrations (Fig. 3D) were most pronounced at the intermediate transect stations (stations 5-12) and reflect the presence of green algae at the shelf-slope break. Highest near-surface ammonium concentrations were measured here and may partially explain phytoplankton compositional variations along

Table 3. *Contributions of diatoms, green algae, dinoflagellates and "other" phytoplankton to integrated chlorophyll a biomass ($\mu g/m^2$) at stations sampled in the Bering Sea during July 1984. Values in parentheses are the percent contributions to total chlorophyll a biomass.*

Station	Chl *a*	Diatoms	Green Algae	Dinofl	Other
2	19,310 (100%)	9,774 (51%)	3,061 (16%)	226 (1%)	6,249 (32%)
3	34,540 (100%)	19,611 (57%)	5,183 (15%)	503 (1%)	9,243 (27%)
4	39,575 (100%)	19,866 (50%)	3,901 (10%)	450 (1%)	15,358 (39%)
5	12,425 (100%)	3,538 (28%)	4,491 (36%)	226 (2%)	4,170 (34%)
6	20,458 (100%)	7,238 (35%)	5,590 (27%)	206 (1%)	7,424 (37%)
7	11,468 (100%)	4,373 (38%)	2,515 (22%)	165 (1%)	4,415 (39%)
8	10,733 (100%)	2,137 (20%)	4,142 (39%)	171 (2%)	4,283 (39%)
9	19,070 (100%)	6,606 (35%)	4,430 (23%)	100 (1%)	7,934 (41%)
10	15,183 (100%)	9,446 (62%)	2,674 (18%)	35 (0%)	3,063 (20%)
11	62,518 (100%)	39,177 (63%)	2,366 (4%)	44 (0%)	20,931 (33%)
12	45,140 (100%)	46,146 (<100%)	2,294 (5%)	0 (0%)	0 (0%)
13	137,375 (100%)	81,686 (59%)	1,808 (1%)	0 (0%)	53,881 (40%)
14	60,923 (100%)	41,130 (68%)	410 (1%)	0 (0%)	19,383 (31%)

Table 3. *Continued.*

Station	Chl *a*	Diatoms	Green Algae	Dinofl	Other
15	28,750 (100%)	18,038 (63%)	317 (1%)	35 (0%)	10,360 (36%)
16	109,685 (100%)	78,625 (72%)	602 (1%)	118 (0%)	30,340 (27%)
17	37,585 (100%)	26,196 (70%)	706 (2%)	53 (0%)	10,630 (28%)
18	34,960 (100%)	27,672 (79%)	384 (1%)	0 (0%)	6,904 (20%)
19	24,118 (100%)	16,271 (67%)	637 (3%)	35 (0%)	7,175 (30%)
20	14,863 (100%)	8,217 (55%)	1,328 (9%)	259 (2%)	5,059 (34%)
21	12,160 (100%)	4,646 (38%)	2,294 (19%)	224 (2%)	4,996 (41%)
22	23,865 (100%)	8,922 (37%)	5,485 (23%)	241 (1%)	9,217 (39%)
23	13,530 (100%)	3,250 (24%)	3,826 (28%)	447 (3%)	6,007 (45%)
24	13,595 (100%)	4,495 (33%)	2,456 (18%)	162 (1%)	6,482 (48%)
25	19,593 (100%)	8,639 (44%)	3,323 (17%)	235 (1%)	7,396 (38%)
26	18,883 (100%)	7,450 (39%)	3,512 (19%)	429 (2%)	7,492 (40%)

the transect. In comparison, dinoflagellates were most abundant along the southern portion of the transect (stations 3, 25, 26, and 4; Fig. 3C), just north of the Aleutian Islands. Based on the distributions of fucoxanthin, chlorophyll *c* and diadinoxanthin, diatoms appeared to be the dominant algal group for the region surveyed. Thus, the HPLC data confirmed the microscopic count data from this expedition, which showed that diatoms (especially *Chaetoceros* spp., *Thalassiosira* spp. and *Rhizosolenia* spp.) dominated the summertime phytoplankton population in the Bering Sea.

The photoadaptative state or "light history" of a natural phytoplankton assemblage may be deduced by examining the distribution of photoprotectant carotenoids. Carotenoids function in photosynthesis as photoprotectants by preventing the photooxidation of chlorophylls at high light intensities (Paerl et al. 1983):

$$\text{Chl } a + h\nu \rightarrow \text{Chl } a^{t}$$
$$\text{Chl } a + O_2 \rightarrow \text{Chl } a + O_2^{t}$$

The superscript "t" designates a triple-state condition and the triplet oxygen state can result in the photooxidation of chlorophyll *a*. Carotenoids protect the photosynthetic apparatus from photodestruction by returning both chlorophyll *a* and O_2 to their respective ground states and dissipating the resultant energy as heat:

$$\text{Chl } a^{t} + \text{CAR} \rightarrow \text{Chl } a^{\circ} + \text{CAR}^{t}$$
$$\text{CAR}^{t} \rightarrow \text{CAR}^{\circ} + \text{heat}$$

and/or

$$O_2^{t} + \text{CAR} \rightarrow O_2^{\circ} + \text{CAR}^{t}$$
$$\text{CAR}^{t} \rightarrow \text{CAR}^{\circ} + \text{heat}$$

The carotenoids α,β-carotene and zeaxanthin are thought to play an important role as photoprotectants in phytoplankton (see Grumbach et al. 1978; Paerl et al. 1983).

Several carotenoids are capable of undergoing light-induced reversible epoxidation and de-epoxidation reactions, a process known as "rapid xanthophyll cycling." While the precise function of these reactions is unclear (Jeffrey 1980), they may function in photoprotection. In the golden-brown algae (diatoms, dinoflagellates, prymnsiophytes, and chrysophytes), the carotenoid diadinoxanthin is converted to diatoxanthin under high-light conditions. This reaction occurs quite rapidly, on time scales of seconds to minutes (Welschmeyer 1986). It has also been observed, however, that the ratio of diadinoxanthin to chlorophyll *a* increases with increasing light intensity on considerably longer time scales (Mandelli 1969, 1972; Hagar and Stransky 1970; Stransky and Hagar 1970). Thus, the diadinoxanthin-to-chlorophyll *a* ratio may be useful for predicting phytoplankton light histories on time scales of hours to days. Laboratory studies have shown that diadinoxanthin is not active in photosynthesis (Tanada 1951; Mann and Myers 1968; Haxo 1985).

The fact that the phytoplankton located in the northern Bering Sea were dominated by diatoms (Table 3 and Fig. 3B) creates a natural experiment for examining the influence of light on the pigment composition. A comparison of the ratios (w:w) of fucoxanthin and diadinoxanthin to chlorophyll *a* for stations 14-16 is given in Table 4. At all three stations, fucoxanthin to chlorophyll *a* ratios increased 1.1- to 2.0-fold as a function of depth, suggestive of a photoadaptative response by the diatoms to the low intensities of light present deep in the water column. Laboratory studies conducted with the diatom *Skeletonema costatum* have demonstrated that fucoxanthin-to-chlorophyll *a* ratios increase under low-light conditions and that this change represents increases in the proportion of light-harvesting pigment-protein complexes in the photosynthetic unit (Gallagher et al. 1984). In contrast, ratios of diadinoxanthin to chlorophyll *a* decreased twofold to fivefold with increasing depth. These data provide additional evidence that diadinoxanthin has a photoprotective function in diatoms. The P-I parameters measured

Table 4. *Comparison of fucoxanthin- and diadinoxanthin-to-chlorophyll a ratios for three diatom-dominated stations sampled in the Bering Sea during July 1984.*

Station No.	Depth (m)	Fucoxanthin / Chlorophyll *a*	Diadinoxanthin / Chlorophyll *a*
14			
	0	0.66	0.12
	5	0.63	0.11
	10	0.69	0.07
	15	0.70	0.06
	20	0.75	0.07
	25	0.77	0.08
	30	0.71	0.06
	35	0.73	0.06
	40	0.72	0.06
15			
	0	0.37	0.26
	10	0.50	0.55
	15	0.40	0.25
	25	0.69	0.46
	30	0.69	0.19
	35	0.62	0.04
	40	0.59	0.04
	45	0.92	0.07
	50	1.08	0.07
	55	1.01	0.05
16			
	0	0.62	0.13
	10	0.57	0.12
	15	0.83	0.15
	20	0.75	0.06
	25	0.80	0.05
	30	0.78	0.06
	35	0.80	0.06
	40	0.85	0.05
	45	0.90	0.05
	50	0.95	0.05

during this study also indicate the phytoplankton collected from surface waters were high-light adapted, as evidenced by the lack of photoinhibition. Laboratory studies performed with diatom and green algal clones have shown that photoprotectant carotenoids are labeled with a higher degree of specific radioactivity than chlorophyll *a* or the photosynthetic accessory pigments (Anderson et al. 1960; Grumbach et al. 1978; Goericke and Welschmeyer 1987). The field measurements presented here support the results of the algal labeling experiments by demonstrating that diadinoxanthin comprises a very dynamic pigment pool. Carotene- and chlorophyll *c*-to-chlorophyll *a* ratios exhibited no consistent depth-dependent trends.

Summary

High-performance liquid chromatography (HPLC) was used to quantify the major algal pigments and degradation products extracted from samples collected from the Bering Sea during July 1984 as part of a joint United States-Union of Soviet Socialist Republics research expedition. Chlorophyll *a* concentrations ranged from 10 to 5,000 ng/L (11-140 mg chl a/m^2), with highest concentrations measured on the northern Bering Sea shelf. The quantitatively important accessory pigments present were chlorophyll *c*, diadinoxanthin, and fucoxanthin, reflecting the dominance of diatoms in the Bering Sea during midsummer. Elevated chlorophyll *b* concentrations measured at the shelf-slope break revealed that green algae were an important biomass component at this location. Dinoflagellates, in contrast, were presumed to be a minor contributor to biomass, since peridinin concentrations were low or below the limit of HPLC quantification. Ambient concentrations of nitrate and ammonium appeared to be important in controlling the distributions of diatoms and green algae, respectively. Zooplankton grazing activity was inferred to be greatest on the northern shelf, since the highest phaeophorbide *a* concentrations were measured there. The chlorophyll *a* maximum at most stations was

situated just above the 1% light level, which defined a lower depth limit for biomass accumulation at these stations. At one station in particular, however, vertical mixing appeared to be the dominant variable controlling phytoplankton distributions. Accessory pigment-to-chlorophyll *a* ratios calculated for representative diatom-dominated stations suggest that this group of phytoplankton was photoadapted to the ambient light conditions present in the water column.

Acknowledgments

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PHYTOPLANKTON OF THE BERING SEA, SUMMER 1984

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The U.S. and U.S.S.R. comprehensive research on the ecosystem of the Bering Sea has been carried out since 1977 (Izrael 1983). Under the framework of this multiyear work, one of the objects has been to study marine phytoplankton.

During the 1977 expedition, studies of phytoplankton were preliminary and sketchy; in the northeast zone of the Bering Sea, several bloom species were defined. During the next expedition (June 1981) a detailed qualitative and quantitative study of phytoplankton was carried out in four polygons (Izrael and Tsyban 1987). As a result of the processing of this data, the possibility to evaluate long-term changes in the status of plankton algae communities of the Bering Sea became real. Such analysis was carried out in work on the result of the expedition from 1981 and the results of study of microalgae during the 1930's, 1950's, 1960's, and 1970's (Ventsel and Vasyutina 1987).

Our goal for research in 1984 was to continue the long-term observations and to develop concepts about the composition, quantity, spatial distribution, and size structure of plankton phytocoenosis of the Bering Sea.

Materials and Methods

Material on phytoplankton was collected during the 37th expedition of the research vessel *Akademik Korolev* in July 1984, at four polygons (frontispiece). The southern, eastern, and western polygons were located in a deep-water zone: the south, between the Rat Islands and the Bower Underwater Range; the east, on the eastern periphery of the deepwater region; and the west, along the underwater range Shirshov. The northern polygon was located along the wide continental shelf near St. Lawrence Island. Sampling was carried out by using plastic Niskin bottles from depths 0, 5, 10, 15, 25, 45, 70, and 100 m, and in certain locations in the south and west polygons at 35 and 200 m as well. All together 200 bathometric samples from 26 stations of phytoplanktons were collected and processed.

The bathymetric samples, with volumes of 3-9 L, were concentrated immediately after the sampling by using a system of reverse filtration (Sukhanova 1983) through a 1-μm nucleopore filter (manufactured by the Institute of Nuclear Research of the U.S.S.R. Academy of Sciences, Dubna). In the retrieved sample (volume 17-55 mL), various size and shapes of algae (size less than 20 μm) were those phytoplankton which were deformed or, as a rule, were not preserved in the fixed sample, particularly if the processing was done several hours after the collection of the material.

The cells of the nannoplankton were counted in a 0.01-mL drop of water in a very thoroughly mixed sample. The advantage of studying such a small drop under field conditions is that the height of a drop under glass (size 18 x 18 μm) is comparatively low; consequently, when the drop is examined under a microscope while the ship is moving or when seas are rough, there is almost no chance of it disappearing under the covering of glass. On the ship, we processed the samples by using an MRI-1 microscope (made in Poland), with a magnification of 300 to 800. Along with the count of quantity of

phytoplankton, the size and shapes of its cells were also measured. The species composition of this nannoplankton was not determined during this phase of the work.

After processing the 0.01 mL subsamples, the major portion of the sample was fixed in a Lugol solution (2 x 100 mL per sample), and 5 to 10 days later the samples were finally fixed in a solution of 40% formalin neutralized with chalk (2 x 100 mL per sample).

The processing of fixed concentrations of phytoplankton samplings was carried out in the phytoplankton laboratory of the Institute of South Seas Biology of the Ukrainian Academy of Sciences (Sevastopol) (south and part of the east polygons), and in the Division of Ocean Monitoring of the Laboratory of Environmental and Climate Monitoring of the State Committee of Hydrometeorology and Academy of Sciences of the U.S.S.R. (Moscow). The material was well preserved before its processing, and there was no development of bacteria in the samples.

The final volume of fixed samples was from 0.8 to 13 mL. The count of phytoplankton was carried out in drops having a volume of 0.01-0.05 mL (taken from thoroughly mixed samples) with the use of electron microscopes (produced in the U.S.S.R.) having a magnification of 250 to 1,300. Such a ratio of volumes of samples and subsamples in accordance with the work (Kol'Tsova et al. 1979) allows us to count the quantity of phytoplankton with a probable error in results of 20% at a confidence level of 95%. Along with the count of cells they were also measured for size.

A count of the biomass of phytoplankton in the south polygon was carried out according to "real" volumes of the algae cells, and in the other polygons (Senichkina 1978; Senichkina 1986a, b), with the use of average values for the results of each measurement (material collected in 1981 (Ventsel and Vasyutina 1987) and 1984), and using sources in the literature (Semica 1981). No count of large (more than 50 microns) forms of algae in all the sediment of the sample was carried out and occasional instances of these cells in the drops under examination were excluded from the sum total of the biomass of phytoplankton in the sample.

Comparison of the results obtained in various laboratories shows that there were no significant differences between these findings and that any inconsistencies were due to very small differences in the methodology of processing and individual characteristics of the specialist doing the work.

The count of statistical characteristics of phytoplankton for Tables 3 and 4 was carried out on an IBM model ES-1010 by L.A. Manzhos, who works in the Phytoplankton Laboratory of the Institute of Southern Seas Biology.

Results

In June 1984, we discovered 209 species and subspecies of phytoplankton, as well as small flagellate algae and olive-green cells in the Bering Sea. The basic phytocene was composed of diatomic (109 species) and pyrophytic (77 species) algae. Twelve species were golden algae, and 11 were other species of algae (green, multiflagellate, euglena species; Table 1). Many cells (particularly small without spines) were classified to the genus name, and the overall number of species of phytoplankton, on the whole, was lowered.

The flora of all polygons was dominated by diatoms, and the species of other categories (as well as the absolute quantity of species) came in the following order: peridynes, golden, and algae of other taxonomic groups. The maximum overall number of species for diatoms was noted in the north polygon (67%); for peridina, in the west polygon (38%); for the golden, in the south polygon (10%); and for species of other taxa, in the north polygon (9%) (Table 1).

A rich diversity of flora was found in each polygon. For instance, at just one south

Table 1. *Systematic composition of phytoplankton in the Bering Sea in July 1984.*

Parameters	Section	Polygon South	East	West	North	Total
Number of species	Diatomic	42	55	50	51	109
	Pyrophytic	21	37	39	16	77
	Golden	8	5	8	2	12
	Others[a]	5	5	5	7	11
Total		76	102	102	76	209
Ratio (%)	Diatomic	55	54	49	67	52
	Pyrophytic	28	36	38	21	37
	Golden	10	5	8	3	6
	Others[a]	7	5	5	9	5
Total		100	100	100	100	100

[a]Others = green, multiflagellate, and euglena algae.

polygon there was more than one third of the overall quantity of species of plankton algae: 32% diatomic, 37% pyrophytic, 41% golden, 36% "others." There were only six species of algae that were common to all polygons; the diatomic species *Chaetoceros septentrionalis, Nitzschia closterium, Nitzschia seriata, Rhizosolenia alata*, and the golden species *Coccolithus huxleyi* are typical for the Bering Sea. The eugenic species, *Eutreptia* sp. was also encountered.

Among the small flagellate algae, 38 types were distinguished by their form and the size of the cells (Table 2). The most varied in size were the conical cells, and in descending order of variation of size there follows ellipsoid, round, and divided conic forms.

Among the small flagellates of various forms, the most commonly encountered were small cells (Table 2). These algae were distinguished also by a large ratio of the surface to the volume (Table 2).

The overall number of phytoplankton on the surface of the sea varied from 2.739 x 10^9 kL/m^2 (station 7) to 63.236 x 10^9 kL/m^2 (station 16). The distribution of the examined indicators along the Bering Sea water column in gradations divided among the logarithmic scale is presented in Fig. 1. High values for the number of algae (more than 20 x 10^9 kL/m^2) were registered on or above the shelf in the area near Cape Chukotka and St. Lawrence Island (stations 13, 14, 15, 16), and in the open part of the sea, at station 25 (39.827 x 10^9 kL/m^2). There was less phytoplankton at station 17 (19.256 x 10^9 kL/m^2). Along most of the observed water column, the quantity of cells did not differ significantly, from 4 x 10^9 to 9 x 10^9 kL/m^2 and when outside these specific stations (Fig. 1).

The distribution of the total surface biomass of phytoplankton in the studied water column, in gradations divided along the logarithmic scale, is presented in Fig. 2. The minimum value for 1.181 g/m^2 was noted at station 5, and

Table 2. *Frequency of encounter of small flagellate algae of various forms and sizes of cells in the Bering Sea (July 1984).*

Form	Size (μm)	Volume (μm^3)	Estimated diameter (μm)	Estimated surface area (μm^2)	Frequency of encounter in % of total no. of stations
Round	3	14	3.0	28	100
	5	65	5.0	79	100
	8	268	8.0	201	100
	11	697	11.0	380	96
	14	1,437	14.0	616	89
	16	2,145	16.0	804	39
	19	3,591	19.0	1,134	15
Ellipsoid	3x6	28	4.0	50	92
	6x8	149	6.5	133	23
	6x11	205	7.5	177	89
	8x14	261	8.0	201	8
	6x11	367	9.0	254	77
	8x14	467	9.5	287	35
	8x16	533	10.0	314	23
	11x14	887	12.0	452	96
	11x16	1,013	12.5	491	54
	11x19	1,203	13.0	531	8
	14x16	1,643	14.5	661	65
	14x19	1,951	15.5	755	4
	16x19	2,546	17.0	908	27
Conical	3x3	7	2.5	20	73
	3x6	14	3.0	28	100
	3x9	21	3.5	38	4
	3x11	26	3.5	38	27
	5x20	133	6.5	133	4
	6x6	56	4.5	64	73
	6x8	75	5.0	79	4
	6x11	103	6.0	113	92
	6x14	131	6.5	133	15
	6x16	149	6.5	133	4
	6x19	168	7.0	154	19
	8x8	133	6.5	133	4
	8x14	233	7.5	177	8
	8x16	267	8.0	201	12
	8x19	317	8.5	227	39
	11x16	507	10.0	314	8

Table 2. *Continued.*

Form	Size (μm)	Volume (μm^3)	Estimated diameter (μm)	Estimated surface area (μm^2)	Frequency of encounter in % of total no. of stations
Conical	14x14	719	11.0	380	4
	14x19	975	12.5	491	4
Divided-Conic	4x5	28	4.0	50	50

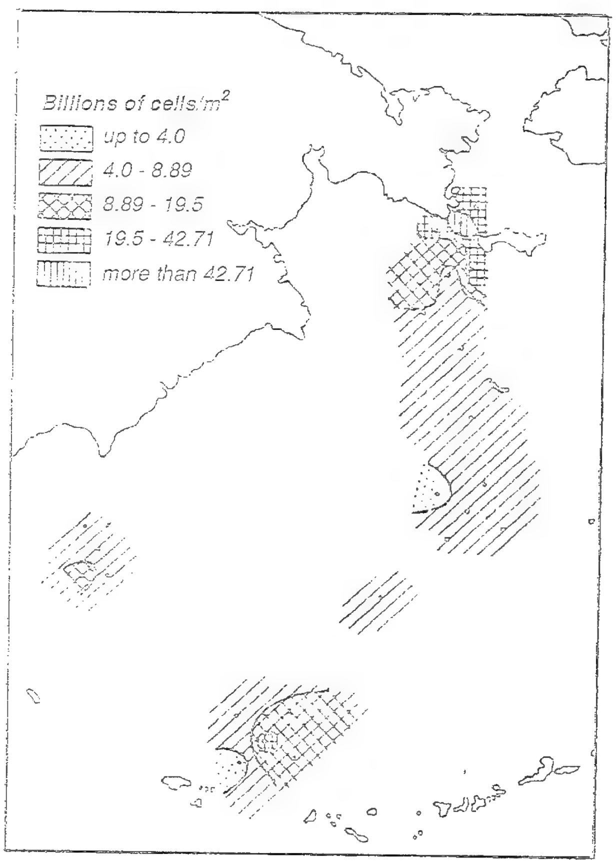


Fig. 1. Number of phytoplankton located under the surface of the sea.

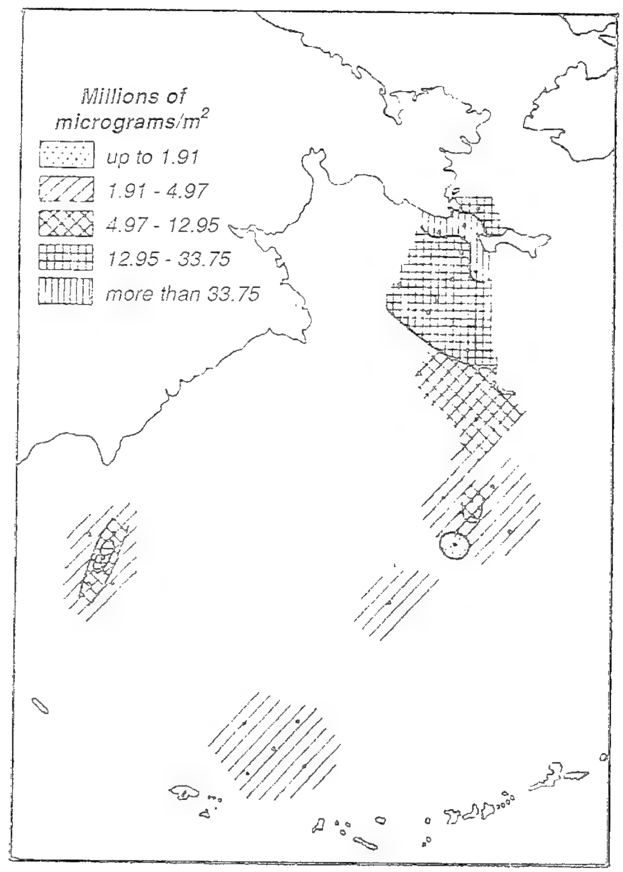


Fig. 2. Biomass of phytoplankton on the surface of the Bering Sea.

the maximum (54.479 g/m^2) at station 16. A significant increase in the phytoplankton biomass was noticed in all areas located above the shelf and at station 21 (25.272 g/m^2). At stations 6, 10, 20, and 22, the biomass changed from 5 to 13 g/m^2. The remaining areas of the Bering Sea were characterized by a small variation in the biomass of algae within the range of 2-5 g/m^2.

The vertical distribution of the quantity and biomass of the phytoplankton in all the areas surveyed showed a significant variation in species. As a rule, the vertical profile of the quantity of algae was characterized by several maximums and minimums. Most often, the maximum numbers coincided with maximum biomass; however, at a number of stations, these maximums were found at depths. No distinct tendencies to form maximums or minimums in phytoplankton at varying depths (in the limits 0-45, 0-70 m) were noted. At greater depths (100 and 200 m), there was always comparatively little phytoplankton.

A general conception of the distribution along vertical lines of phytoplankton in the Bering Sea is given by an analysis of the average data for the studied regions of the sea (Table 3). Thus, for the southern region, on the average, the quantity and biomass of algae were high (numbering more than 100 million kL/m^3, biomass more than 50 mg/m^3) in the layer from 0-15 m. Below 15 m, there was less phytoplankton. In the west polygon and in the eastern portion of the sea, an increase in the quantity of phytoplankton was noted in the 0-25-m layer, below which there was less algae. In the northern region, on the average, phytoplankton was uniformly distributed in the limits of 0-45 m and was distinguished by large values for both numbers and biomass. At a depth of 7 m, the quantity of algae decreased somewhat.

The average volume of algae cells in the areas under observation in the Bering Sea aquatoria changed insignificantly (Table 3). The vertical profile of this indicator also showed great stability. In the northern region there was also observed a weak tendency toward an increase in the average cell volume.

In the open portions of the Bering Sea (south, east, west polygons and stations 4, 10) a significant portion of the overall number and biomass of phytoplankton was composed of small flagellates (Table 4). Among other groups of phytoplankton in this area at individual locations, we noted an increase in the numbers of several species of diatom, golden, and pyrophyte algae for which small cell sizes were typical. On the whole (excluding the quantities of collected groups of small flagellates), the open waters of the sea during the research period were distinguished with a significant uniform number and distribution of both quantity and biomass of phytoplankton species.

In the shelf areas of the Bering Sea, diatoms predominated, particularly the species of the genera *Chaetoceros* and *Thalassiosira*. An increase in the quantity of algae of other divisions was not noted. The overall quantity and biomass of phytoplankton in the area located over the shelf (in contrast to open waters) was usually formed through the abundance of 1, 2, and 3 dominant species.

Various species of diatoms that developed in the area above the shelf predominated in the plankton at various stations and depths. Thus, the complex consisting of the species *Chaetoceros socialis, Chaetoceros furcellatus, Thalassiosira nordenskioldii, Fragillaria oceanica*, and *Thalassiosira* cf. *antarctica* dominated in the entire water column at stations 14 and 16, and in the subsurface layer of water at the other station located above the shelf, as well as at the west polygon stations 21, 22, and 23 (Fig. 3). In the surface layer of the water above the shelf, the species *Chaetoceros compressus, Chaetocerus subsecundus, Chaetocerus concavicornis*, and *Leptocylindrus danicus* predominated. At stations 21, 22, and 23 in the surface layer of water, the main mass was small flagellate algae.

Table 3. *Vertical distribution of phytoplankton in various regions of the Bering Sea in July 1984.*

Polygon	Level	No. of observations	Quantity (millions of cells/m^3) min.	max.	avg.	Biomas (microgram/m^3) min.	max.	avg.	Volume of cells, μm^3 min.	max.	avg.
South	0	5	19	1,419	409	19	137	88	96	994	496
	5	5	76	560	223	54	119	82	181	788	502
	10	5	20	1,353	349	45	114	78	184	3,465	1,106
	15	5	40	2,369	546	43	138	75	58	1,061	610
	25	5	32	171	84	25	52	42	231	1,367	686
	45	7[a]	46	217	105	20	65	37	124	1,098	466
	70	5	24	183	64	5	26	13	142	344	247
	100	4	16	130	73	4	15	9	37	302	182
	200	1	-	-	26	-	-	2	-	-	73
East, stations 4, 10	0	7	62	338	185	43	329	122	342	974	617
	5	7	10	178	95	14	244	79	182	1,783	940
	10	7	26	227	90	24	265	84	284	2,244	1,069
	15	7	14	191	94	11	165	78	134	2,179	997
	25	7	37	222	90	13	198	75	281	1,263	783
	45	9[a]	31	95	67	9	194	60	97	3,528	1,122
	70	7	4	44	21	1	29	9	73	2,618	740
	100	6	7	49	27	3	19	7	64	851	330
North, stations 11, 14, 18, 19	0	9	85	2,293	499	223	914	516	398	4,547	1,852
	5	9	81	2,515	462	151	1,531	532	608	7,606	2,445
	10	9	29	2,061	445	22	1,338	563	649	7,014	2,134
	15	9	44	2,373	666	298	1,333	662	561	7,354	2,131
	25	9	77	1,175	554	277	1,275	838	1,031	6,497	2,508
	45	9	85	597	306	87	1,019	491	743	2,739	1,750
	70	5	30	200	97	19	267	146	627	3,511	1,956
West	0	5	93	1,389	392	51	84	64	43	701	431
	5	5	97	343	207	37	570	197	120	3,776	1,339
	10	5	85	391	157	33	112	83	287	1,041	658
	15	5	31	396	128	16	148	61	300	1,346	683
	25	5	89	337	147	17	117	69	192	881	542
	45	5	21	83	52	11	86	40	233	1,191	716
	70	5	9	78	39	6	32	17	162	1,879	696
	100	4	11	40	26	5	16	12	319	1,023	540
	200	3	9	13	11	4	12	8	395	1,315	741

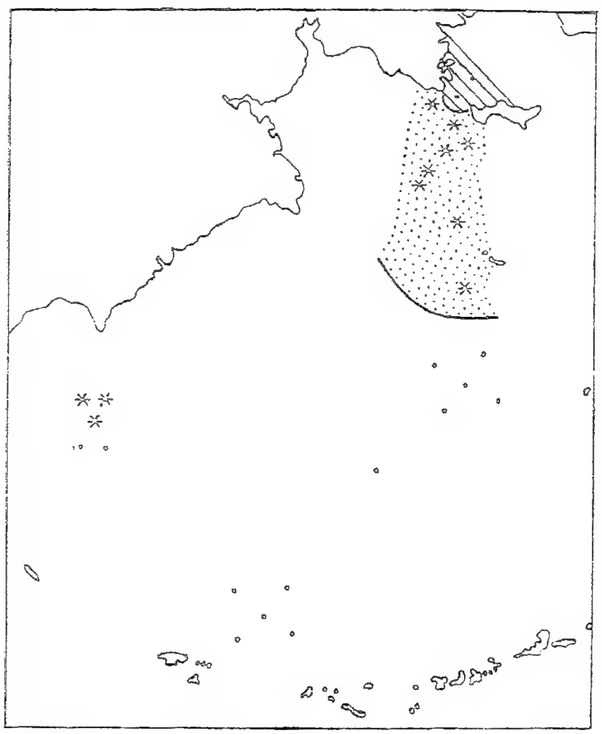
[a]with regard to observations made at the 35 m level

Table 4. *Deposit of small flagellate algae into the overall number and biomass of phytoplankton in various regions of the Bering Sea in July 1984.*

Polygon	Level (m)	Number min.	Number max.	% of total: avg.	min.	Biomass max.	Biomass avg.
South	0	30	99	76	3	60	27
	5	44	99	78	3	44	21
	10	35	99	73	2	52	16
	15	32	99	71	2	34	15
	25	44	95	78	6	29	18
	45	52	99	85	3	85	31
	70	81	97	91	9	34	21
	100	86	98	93	26	49	36
	200	-	-	98	-	-	51
East, stations 4, 10	0	47	96	82	8	29	22
	5	72	96	84	5	51	23
	10	79	97	89	10	58	30
	15	65	94	86	10	43	23
	25	13	92	63	2	31	17
	45	16	99	83	1	71	27
	70	72	98	88	8	89	44
	100	62	99	91	9	50	23
West	0	80	>99	92	14	52	30
	5	76	>99	89	6	31	15
	10	69	97	86	5	39	22
	15	77	94	89	11	32	21
	25	59	96	81	15	36	25
	45	42	92	67	8	20	14
	70	49	97	76	5	40	24
	100	72	95	82	7	26	16
	200	83	86	84	10	43	28
North, stations 11, 14, 18, 19	0	3	34	15	<1	7	3
	5	1	22	9	<1	2	<1
	10	1	51	22	<1	18	5
	15	1	21	9	<1	3	2
	25	1	22	6	<1	2	<1
	45	1	7	4	<1	4	1
	70	12	73	33	2	21	6

Discussion of Results

We compared the results of the 1981 (Ventsel and Vasyutina 1987) study of phytoplankton, including the flora, quantity of phytoplankton, and composition of mass species, with data contained in the literature from the 1930's to 1970's. During the course of the analysis, we noted no long-term changes in the state of phytocoenosis in studied water columns for the past 30-50 years. The research into long-term changes of the phytoplankton was continued in the 1984 expedition and the results obtained were compared with materials from 1981 (Korsak et al. 1987; Ventsel and Vasyutina 1987).



* Stations with a marked shift in dense-concentrating algae species along the vertical

Region in which <u>Chaetoceros</u> <u>socialis</u> and associated species predominated throughout the water column

Region of vegetation in the surface layer of the water for <u>C. compressus</u>, <u>C. subsecundus</u>, <u>C. concavicornis</u>, <u>Leptocylindrus</u> <u>danicus</u>

Fig. 3. Distribution of dense-concentrating phytoplankton species.

In the Bering Sea in 1984, as well as in 1981, we discovered a large quantity of species that belong to various groups of algae. In both instances the greatest variation occurred in the diatomic and peridine flora. In 1984, we identified several more species of phytoplankton than in 1981 (Korsak et al. 1987; Ventsel and Vasyutina 1987). The results of the study of plankton flora of the Bering Sea in 1984 and their comparison with data from 1981 also showed that the current lists of species are not complete. Taxonomic evidence about such an ecologically important group of phytoplankton as the small flagellate algae is especially fragmentary.

The number of algae species in 1984 at all polygons was greater and the biomass smaller than in 1981 (Table 5 shows the corresponding average arithmetical values and mean square variations). In processing and evaluating the materials in 1981, we determined small flagellate algae numbers in samples fixed with formalin, which could lead to an incomplete quantitative count of this group of organisms. We included small flagellate algae in the quantity of mass groups of phytoplankton in the east and south polygon. Thus, there could be variations in the results obtained in the two studies due to differences in the methods of processing samples. However, on the whole we consider conclusions about the greater quantity and lesser biomass of phytoplankton in 1984 as compared with 1981 to be quite well founded.

In the composition of mass species of phytoplankton in 1981 and 1984, we also observed a certain similarity as well as significant differences. In both cases in the northern part of the ocean the spring and spring-summer groups of species (Saito and Taniguchi 1978, Semica 1981; Ventsel and Vasyutina 1987) predominated: *Chaetoceros furcellatus, Chaetoceros socialis, Fragillaria oceanica, Thallassiosira nordenskioldii*, and *Thalassiosira* cf. *antarctica*. In 1984, *Chaetoceros socialis* greatly predominated, but in 1981, this species was rarely encountered and was found in spore form, while massive

Table 5. *Number of phytoplankton at observation polygons in the Bering Sea in June 1981 and July 1984 (excluding sections and additional stations).*

Index	West				North				East				South			
	1981		1984		1981		1984		1981		1984		1981		1984	
	M	β	M	β	M	β	M	β	M	β	M	β	M	β	M	β
Quantity/m^2 (billions of cells/m^2)	13.5	7.3	8.2	2.9	13.7	7.1	30.9	22.0	3.1	4.0	5.4	2.3	3.7	3.1	14.6	14.7
Biomass/m^2 (grams/m^2)	16.9	8.3	9.5	9.4	37.3	16.3	24.9	16.0	17.0	13.1	3.5	2.1	8.1	7.0	3.5	0.6

development of *Chaetoceros furcellatus* was observed. In addition, in the northern region in 1984, no development of species having large cells was noted, though these (*Thalassiosira* cf. *antarctica*, *Peridinium pellucidum*, and *Gyrodinium lachrima*) were quite commonly found in 1981.

In 1981, *Chaetoceros furcellatus* predominated both in the region of the west polygon, in which during 1984 the small flagellate algae took the dominate positions. In 1981, in several stations of the west polygon, we noted the development of *Chaetoceros concavicornis* and also encountered *Chaetoceros compressus*, which in 1984 was growing in the portion between the north stations along St. Lawrence Island and the east polygon. In the east and south polygon during 1984, compared with 1981, there was almost a complete absence of plankton species with large cells (*Coscinodiscus asteromphalus* v. *subbuliens, Asteromphalus robustus,* and *Peridinium pellucidum*).

Thus, a detailed comparison of the status of plankton phytocoenosis in 1981 and 1984 in each of the polygons studied reveals a series of differences that are probably caused by natural (particularly seasonal) variations. In addition, the limited size of the polygons determines the necessity of a detailed analysis of the mezoscaled spatial changes in the status of phytoplankton in the carrying out of multiyear research.

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SESTON

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Seston biomass represents the total of everything that can be sifted by screen from the water (Kiselev 1969). Determination of seston biomass gave us the opportunity on board the vessel to obtain a picture of the spatial distribution of particles suspended in the water column. Seston is composed of biotic as well as abiotic components. However, the content of the latter in open regions of the ocean is insignificant; the basic portion of seston in these areas is composed of mezoplankton organisms: phytoplankton and zooplankton. The objective of this research was to determine the levels of seston biomass in the pelagia of the Bering Sea, as well as to determine the nonuniformity of its distribution in depths and along the aquatorium of the sea.

Materials and Methods

In the Bering Sea in July 1984, at four polygons and six intermediate stations, we obtained three samples for the determination of seston mass. The station numbers are given in the frontispiece. Samples were taken using a plankton net with an entry opening diameter of 37 cm and with a filter cone made of a capron filter 49 (size of filter pores 168 μm) at the following standard depths: 1,000-750, 750-500, 500-300, 300-200, 200-100, 100-50, 50-25, 25-10, and 10-0 m. The samples concentrated up to 250 mL were fixed in a 4% solution of formalin. The volume of seston was determined by using a Yashnow volumeter according to the quantity of the water sample (Yashnow 1959). The average weight of seston was arbitrarily set at 1.

Results

The seston mass during the period of research in the Bering Sea changed greatly depending on the location of the polygon, stage of seasonal development of the plankton community living in the area, and the depth from which the sample was taken.

The south and west polygons, as well as a portion of the east polygon, were located in areas over great depths, the north polygon, and part of the east polygon (stations 8 and 9), in the area of the northeast Continental Shelf of the Bering Sea.

The horizontal distribution of seston mass at stations, figured according to square meter of water surface, is shown in Fig. 1.

In the 100-m surface layer in the south and west polygons, the quantity of seston varied from 34 to 88 g/m^2. These values did not exceed 50% of the seston mass in the column from 0-1,000 m. No less than 90% was contained in the layer from 0-500 m, where the values varied from 96 to 185 g/m^2.

In the east polygon in the layer from 0-1,000 m, the highest levels of seston biomass were discovered up to 342 g/m^2 at station 5.

The basic quantity was concentrated at depths of 100-500 m and composed approximately 70% of the entire mass of the sample. Up to 25% of the mass was found from 500 to 1,000 m. The increase of the seston biomass in the water column noted at this depth from 100

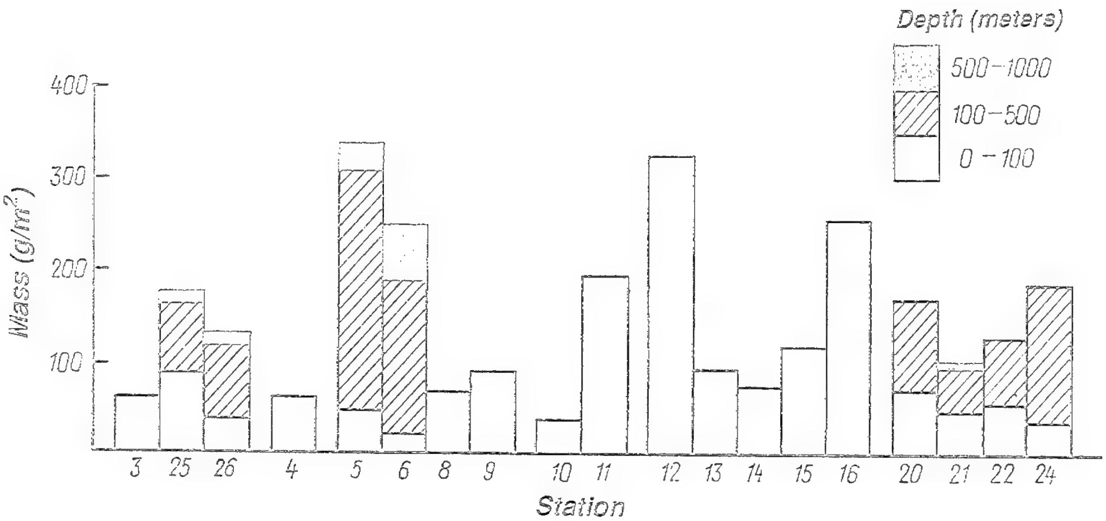

Fig. 1. Seston mass per square meter.

to 1,000 m is probably due to the accumulation of particularly large filter-feeding copepods at these depths along the outer border of the Continental Shelf.

Phytoplankton blooms in the northeast area of the shelf zone of the Bering Sea determined high levels of seston biomass in the northern polygon and in the intermediate stations adjacent to it. The maximum quantity was noted at station 12: 327 g/m^2 (0-65 m depth). The uneven distribution of values of seston mass is apparently due to the mosaic distribution of spots of intensive development of algae.

The vertical distribution of the seston mass at deepwater polygons on the whole had the following general characteristics: large concentrations were discovered in the upper levels (0-45 m), and in lower levels there was a decrease in the biomass. At depths of 100, 200, and 300 m, there was a second maximum, which in several stations exceeded the surface value (Figs. 24). The greatest proportions of seston in deepwater polygons were composed of zooplankton.

In the south polygon, the upper maximum of the seston mass was concentrated in the layer from 0 to 25 m and attained 2,400 mg/m^3 (station 25). Below 50 m, there was an intermediate minimum of 200-300 mg/m^3. In the layer between 200-300 m, a second maximum was observed, and its values did not exceed 470 mg/m^3 (station 26, Fig. 3). The lowest content of seston mass was found at depths of 750-1000 m (3 mg/m^3).

The east polygon was located on the border of the Continental Shelf in the eastern part of the Bering Sea. Stations 5 and 6 were located above depths of approximately 2,600 m, while stations 8 and 9 were located over shallower water. The first group of stations had a double peak character of vertical distribution of seston

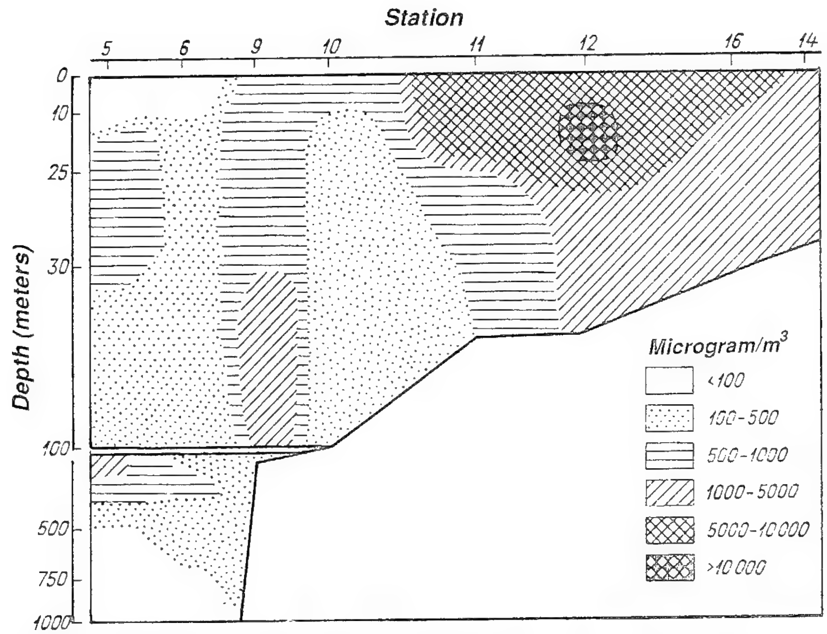

Fig. 2. Vertical distribution of seston mass in in the east-north section.

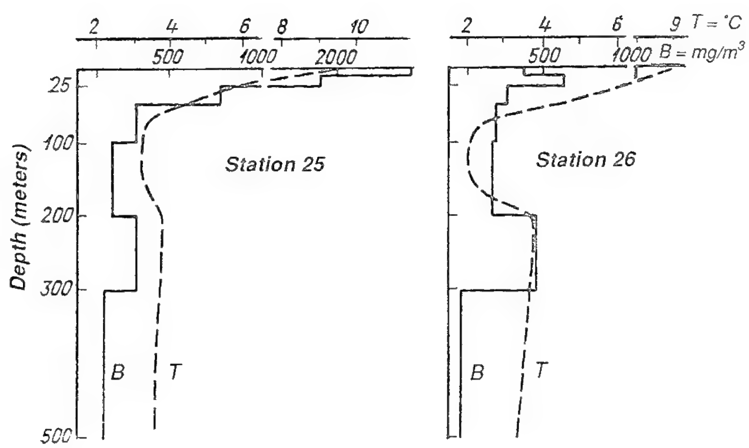

Fig. 3. Vertical distribution of seston mass (B) and temperatures (T) at stations in the south polygon.

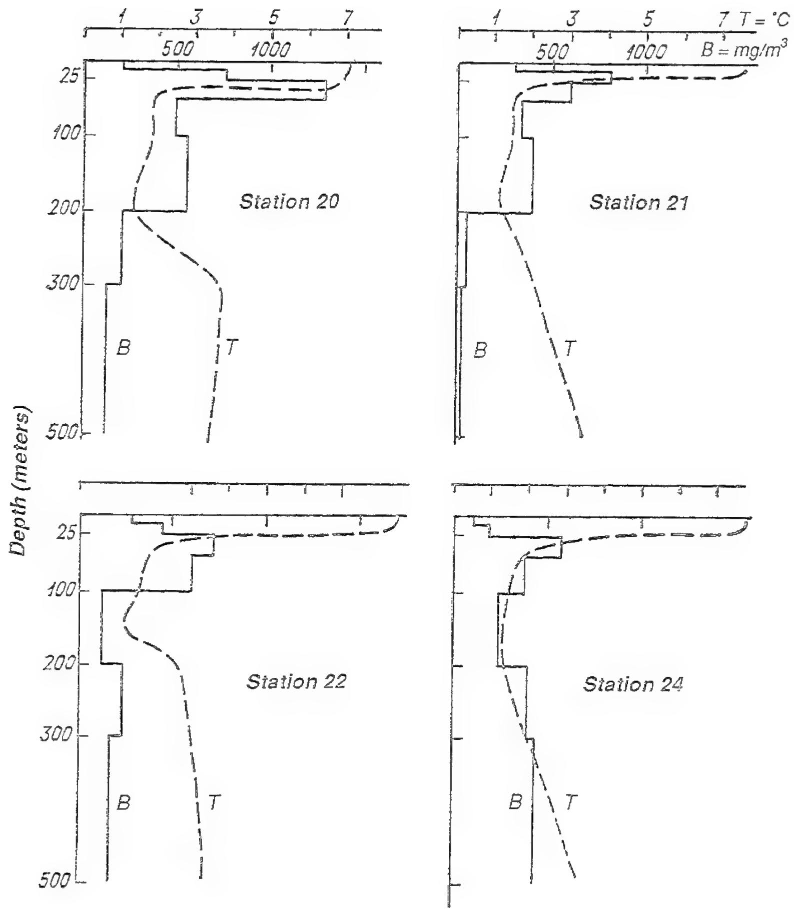

Fig. 4. Vertical distribution of seston mass (B) and temperatures (T) at stations in the west polygon.

mass. The basic mass was concentrated lower than 100 m in depth. At station 5, in the 25-50 m layer, the values did not exceed 950 mg/m^3, and at a depth of 100-200 m, 1,120 mg/m^3 (Fig. 2). At shallow water stations, the values varied from 440 to 1,050 mg/m^3.

The high concentrations of phytoplankton in the north polygon determined high levels of seston biomass at all depths from the bottom to the surface. At station number 12 in the surface water (0-25 m) concentration was 12 g/m^3. In this area, the values did not go below 800 mg/m^3 (Figs. 2 and 5). The vertical distribution of the seston mass in the west polygon was similar to the south polygon.

Conclusions

1. The value sizes for the seston mass in the polygons studied characterized the Bering Sea as a highly productive region of the World Ocean.

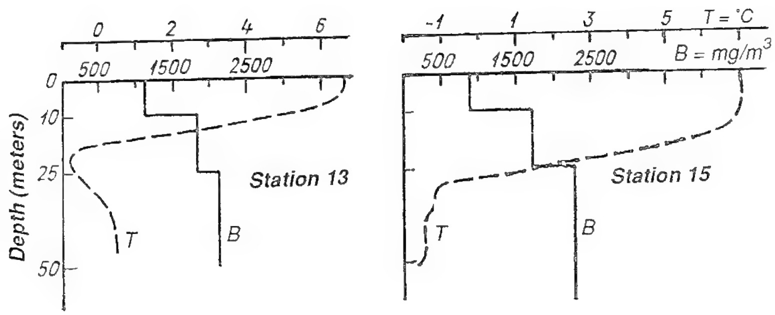

Fig. 5. Vertical distribution of seston mass (B) and temperatures (T) at stations in the north polygon.

2. The maximum levels of seston mass were found in the northeast Continental Shelf of the Bering Sea (north polygon) and in deepwater areas adjacent to its outer border (east polygon).

3. The vertical distribution of the seston mass in deepwater areas of the Bering Sea had a two-peak character. The first maximum was located in the surface (0-45 m) layer, and the second, in the 100-300-m layer.

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MESOZOOPLANKTON

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One of the key aspects of the analysis of the state of a marine ecosystem is the determination of the changes in its structural and functional characteristics. An important part of this research is the study of the qualitative and quantitative indicators of the state of the zooplankton community—a study which plays an active role in the functioning of the ecosystem (Izrael 1981). The present research is aimed at establishing the natural variability levels of the structure and functioning of the mesozooplankton community of the Bering Sea, a highly productive region of the ocean not directly subjected to pollution sources.

The study of the Bering Sea zooplankton began at the turn of the century. Expeditions at that time did not include detailed studies of the zooplankton community of the basin; therefore, the data were taken in small quantities and at individual points (Willey 1920; Johnson 1937; Wilson 1950). The establishment in 1925 of the Pacific Ocean Institute of Fishery and Oceanography began a systematic study of the Bering Sea, prompted by an urgent need to assess the nutritive base of the fish of the Far Eastern seas (Stepanova 1937; Moiseev and Zalesskiy 1982).

After World War II, Soviet scientific institutions developed a systematic study of various aspects of the biology of the Bering Sea. Starting in 1950, the Oceanology Institute and Pacific Ocean Institute of Fishery and Oceanography began expeditions such as the Bering Sea Commercial and Herring Expeditions (Vinogradov 1954, 1956; Geynrikh 1957a,b, 1958; Mednikov 1957; Meshcheryakov 1964, 1970a, b).

At the same time, other governments were also conducting studies. In 1947, an American expedition on the ES *Nereis* (Johnson 1951) worked in the Bering Sea, and starting in 1950, Japanese scientists of Hokkaido University began a 15-year study mainly on the distribution and functional characteristics of surface (0-150 m) plankton over the entire water area of the sea (Nemoto 1963; Omori 1965; Minoda 1971; Motoda and Minoda 1974; Ikeda and Motoda 1978). The PROBES interdisciplinary project (USA), which ran from 1976 to 1982, was devoted to a study of the ecological aspects of the existence of the biocoenosis of the shelf of the southeastern portion of the Bering Sea (Cooney 1981; Cooney and Coyle 1982; Smith 1986; Walsh and McRoy 1986).

The present study is within the framework of the U.S.-U.S.S.R. Joint Research on the Ecosystem of the Bering Sea, started in 1979 on the RV *Volna* (Izrael 1983). The study is distinctive from previous studies of the Bering Sea mesozooplankton in that it involved analyzing data obtained with the aid of water samplers. The samplers made it possible to take into account the small-sized component of the zooplankton, including *Sarcodina* protozoans, nauplii, and younger copepodite stages of small copepods, rotifers, and other organisms poorly caught in plankton nets. The polygons that we studied, which in our view were located in the most characteristic hydrologic regions of the sea, represented a

general picture of the distribution of the Bering Sea mesozooplankton community.

Material and Methods

During the Second Joint U.S.-U.S.S.R. Expedition to the Bering Sea in July 1984, mesozooplankton samples were taken with a 200 L metallic water sampler from depths of 0, 10, 25, 45, 70, 100, 150, and 200 m.

The volume of water (180 L) that remained after removal of the samples from the water sampler for determining the primary production and the phytoplankton and microzooplankton was filtered through a net of synthetic gauze No. 76 with a mesh size of 60 μm. The concentrated material was fixed with 4% formaldehyde. A total of 152 samples of mesozooplankton were obtained at 24 stations.

The material was processed in the standard manner (Tsyban 1980, 1982) by using an MBS-9 binocular microscope. First, large forms more than 5 mm in size were removed from the sample, identified, and measured. Then the volume of the sample was brought up to 50-100 mL, depending on the plankton concentration, and a portion amounting to not less than 1/10 of the sample was taken with a plunger pipette. If the number of specimens of massive species in the sample was less than 100, the sample was counted fully.

Adult specimens of hydromedusae, copepods, amphipods, euphosids, chaetognaths, and appendicularians were identified to species, and the rest, to larger taxa. In Calanoida and Euphausiacea, all the age stages were counted separately; in Cyclopoida and Harpacticoida, adult males and females were distinguished, and nauplii and copepodites were counted together. The biomass of individual specimens was determined from weight tables of Bering Sea plankters (Lubny-Gertsyk 1953) and nomograms for determining the weight of aquatic organisms from body length and shape.

Results

Horizontal Distribution of Mesozooplankton

Analysis of the samples revealed 49 taxonomic units of aquatic organisms (Table 1). Crustaceans of order Copepoda were the most numerous group qualitatively and quantitatively. The most characteristic and massive representatives of this group during the study period in the Bering Sea were the subarctic species *Calanus plumchrus*, *C. glacialis*, and *Eucalanus bungii bungii*, as well as the boreal species *C. cristatus, Pseudocalanus minutus, Microcalanus pygmaeus, Metridia pacifica, Oithona similis*, and *Oncaea borealis*.

Analysis of the structure of the mesozooplankton community of the 200-m surface layer showed that on average, copepods account for about 90% of its total numbers and biomass. The frequency of occurrence and the abundance levels of other aquatic organisms indicate that they play a secondary role in the distribution of the quantitative characteristics of the entire community inhabiting the surface waters in the south, east, and west polygons, which were over deep sea. Larval planktonic stages of development of bottom organisms (meroplankton), as well as medusae, chaetognaths, and appendicularians comprised a significant portion of the plankton only in isolated cases in the shoal of the northeastern shelf of the Bering Sea.

In the south, east, and west polygons, specimens of species of the southern Bering Sea oceanic grouping (Vinogradov 1956) and the eurybiotic epipelagic species *Oithona similis* and *Pseudocalanus minutus* dominated in the mesozooplankton community. The oceanic grouping includes the large filter-feeding copepods *Calanus cristatus, C. plumchrus*, and *E. bungii*, as well as *Microcalanus pacifica, M. pygmaeus, Oncaea borealis*, and *Microsetella rosea*.

Table 2 contains data on the distribution of polygon-averaged values of the numbers and

Table 1. *Frequency of occurrence of species (%) of mesozooplankton.*

No.	Species and groups of species	Polygons			
		South	East	North	West
1.	Foraminifera	70	83	-	13
2.	Radiolaria	15	8	-	22
	HYDROMEDUSAE				
3.	*Aglantha digitale*	10	8	35	31
4.	*Rathkea octopunctata*	-	-	15	-
5.	*Calycopsis nematophora*	3	-	-	-
6.	Siphonophora	13	14	-	16
	ROTATORIA				
7.	*Synchaeta* sp.	-	-	35	-
8.	*Thrichocerca marina*	5	-	-	-
9.	*Nemertini*	-	-	35	-
10.	*Polychaeta* (larvae)	23	22	95	31
11.	*Tomopteris* sp.	-	3	-	6
	MOLLUSCA				
12.	*Gastropoda* (veliger)	15	11	15	16
13.	*Limacina helicina*	35	53	35	53
14.	*Clione limacina*	23	8	5	28
15.	*Bivalvia* (larvae)	10	6	80	-
	OSTRACODA				
16.	*Conchoecia* sp.	18	-	-	6
	COPEPODA				
17.	*Calanus cristatus*	28	36	15	50
18.	*Calanus plumchrus*	48	39	40	66
19.	*Calanus glacialis*	5	11	85	-
20.	*Eucalanus bungii bungii*	53	78	25	69
21.	*Pseudocalanus minutus*	75	69	100	75
22.	*Microcalanus pygmaeus*	70	56	20	75
23.	*Aetideus pacificus*	5	-	-	-
24.	*Pareuchaeta japonica*	10	-	-	-
25.	*Racovitzanus antarcticus*	5	-	-	9
26.	*Scolecithricella minor*	18	11	5	44
27.	*Metridia pacifica*	73	61	40	81
28.	*Pleuromamma abdominalis*	5	-	-	-
29.	*Centropages mcmurrichi*	-	-	25	-

Table 1. *Continued.*

No.	Species and groups of species	Polygons South	East	North	West
30.	*Acartia longiremis*	3	25	30	6
31.	*Oithona similis*	100	100	95	97
32.	*Oithona plumifera*	8	14	-	-
33.	*Oncaea borealis*	90	86	50	100
34.	*Oncaea notopus*	3	-	-	-
35.	*Oncaea minuta*	35	47	10	19
36.	*Harpacticus* sp.	-	-	25	-
37.	*Microsetella rosea*	68	72	25	56
38.	Cirripedia (larvae)	8	-	45	-
AMPHIPODA					
39.	*Parathemisto pacifica*	15	8	-	13
EUPHAUSIACEA					
40.	Euphausiacea (larvae)	3	14	25	17
41.	*Thysanoessa inermis*	-	-	-	3
42.	*Thysanoessa longipes*	-	3	-	3
43.	Decapoda (larvae)	-	22	10	-
44.	Bryozoa (larvae)	10	8	-	-
45.	Echinodermata (larvae)	5	3	50	22
CHAETOGNATHA					
46.	*Parasagitta elegans*	20	14	40	41
47.	*Eukrohnia hamata*	10	3	10	9
TUNICATA					
48.	*Oikopleura labradoriensis*	5	3	70	-
49.	*Fritillaria borealis*	3	17	35	41

biomass of individual dominant species and groups of species, calculated under a square meter of water surface in the 0- to 100-m layer.

The qualitative composition of the mesozooplankton community in the south, east and west polygons differed insignificantly. The distinctive features of the mesozooplankton in the southern polygon include the presence in the surface waters of individual specimens of the boreal bathypelagic species *Aetideus pacificus*, *Gaetanus simplex*, *Pareuchaeta japonica*, *Eukrohnia hamata*, and the subtropical species *Pleuromamma abdominalis* and *Oithona plumifera*, usually found below the 200-m level (Table 1). Their appearance at the surface is due to the fact that the structure of the water masses in this region is affected by vortical formations produced by the arrival of Pacific Ocean waters through the straits between the Aleutians; one can detect the change in the structure of the community that has taken place

Table 2. *Average values of numbers (N, in thousands of specimens/m^2) and biomass (B, g/m^2) of densely concentrating species and groups of species at deepwater stations in the Bering Sea at the 0- to 100-m level.*

No.	Species and groups of species	South N	South B	East N	East B	West N	West B
1.	Foraminifera	12.8	0.2	3.7	0.1	0.4	0.1
2.	Meroplankton	2.5	0.1	0.6	0.1	2.1	0.1
3.	*Calanus cristatus* cop.	0.8	13.2	0.9	15.7	1.4	23.5
4.	*C. plumchrus* cop.	3.0	5.7	2.0	4.4	4.5	4.3
5.	*Eucalanus bungii* cop.	4.5	6.4	5.4	4.4	10.9	5.2
	adults	0.3	2.3	0.4	3.6	-	-
6.	*Pseudocalanus minutus* cop.	15.6	0.4	19.5	0.3	20.0	0.4
	adults	2.7	0.2	1.3	0.1	2.3	0.2
7.	*Microcalanus pygmaeus* cop.	20.9	0.2	10.4	0.1	19.1	0.2
8.	*Metridia pacifica* cop.	13.7	0.7	8.8	0.3	62.0	2.2
	adults	0.2	0.1	0.1	0.1	0.3	0.1
9.	*Calanoida* nauplii	103.4	0.3	97.1	0.4	153.1	0.5
10.	*Oithona similis*	416.3	2.6	405.8	2.6	389.5	2.5
11.	*Oncaea borealis*	54.1	0.4	34.2	0.2	113.3	0.7
12.	*Cyclopoida* nauplii	361.7	1.1	378.0	1.1	292.4	3.5
13.	*Euphausiacea* larvae	-	-	0.2	0.3	1.1	1.4

in one month, during the period between the sampling at stations 1-3 and at station 25. It should be noted first of all that apparently, as a result of a 2-3°C increase in surface-water temperature at station 25, the quantity of the epipelagic *O. similis, Pseudocalanus minutus*, and their nauplii increased significantly. The numbers of foraminifers dropped sharply. Planktonic species such as *Acartia longiremis, Trichocerca marina*, bivalve larvae, mollusks, and immature hydromedusae, which were previously absent or isolated (Vinogradov 1956), were also detected in the samples. Thus, in the southern region of the Bering Sea in the summer period, we observed a trend toward an increase in the density of populations of epipelagic species and propagation of the neritic complex inhabiting the shoal, to deep-sea areas with an increase in surface-water temperature.

In the east polygon, the qualitative composition of the mesozooplankton community characteristic of the deep-sea region of the Bering Sea has been affected by shelf water masses populated with a specific species complex. This applies primarily to the composition of the mesozooplankton at stations located in the area where the depths increase rapidly. Although the distribution of the temperature and salinity levels are the same character here as in surface layers at deep-sea stations, the plankton showed the presence of specimens of *Acartia longiremis* and *Calanus glacialis*, which is included in the northern Bering Sea species grouping (Vinogradov 1956).

In contrast to the qualitative composition of the mesozooplankton, the quantitative indicators of the distribution of the species and species groups dominating in the community and the

age structure of the populations had distinct characteristics in the deep-sea polygons.

The west polygon, where the lowest surface-temperature values for the studied deep-sea areas of the Bering Sea were recorded, was characterized by the earliest stage of development of the mesozooplankton community. In this area, we observed the maximum numbers of nauplial and juvenile copepodite stages, and altogether, also of all the populations of the massive species *C. plumchrus, Eucalanus bungii* and *Microcalanus pacifica*. The age structure of the first two species is shown in Table 3. *C. plumchrus* copepods at stage V dominated in the southern and eastern polygons, and in the western polygon their fraction in the population was substantially lower because of an increase in the quantity mainly of stages II and III. In the population of *E. bungii* in the west polygon, copepodites I-II were dominant, in contrast to the south and east polygons, where stages II-III dominated.

The mean total numbers of *M. pacifica* copepodites in the west polygon were 62,000 organisms/m^2, which is 5-6 times greater than in other deep-sea regions. Also noted here was the maximum density of *Oncaea borealis* population. Minimum quantities of pelagic foraminifers were recorded in the west polygon, but foraminifers are most numerous in the south polygon at an average of 12.8 organisms/m^2 (Table 2).

The east polygon was distinguished by the lowest content of plankton inhabitants, *Microcalanus pygmaeus, Metridia pacifica*, and *Oncaea borealis* of the intermediate cold water layer (45-150 m). To some extent, this is obviously due to a decrease to 100 m in depth at stations located at the boundary of the Bering Sea shelf region.

The northern study area, encompassing the stations of the north polygon, and of sections East-North (stations 10, 11) and North-West (stations 14, 18, and 19), is located above the northeastern shelf of the Bering Sea and differed markedly from the deep-sea polygons in the structural characteristics of the mesozooplankton community populating its water masses.

During the expedition to the northern area, we detected a species complex that consisted primarily of representatives of the northern Bering Sea: *Calanus glacialis*, and neritic groupings, *Acartia longiremis, Synchaeta* sp., juvenile *Aglantha digitalis*, larval stages of bivalves and gastropods, polychaetes, echinoderms, nemerteans, and only at some stations, representatives of the southern Bering Sea oceanic grouping. Foraminifers and radiolarians were absent from the composition of the community at all the stations. The numbers of *Oikopleura labradoriensis* increased appreciably in the plankton.

The structural characteristics of the mesozooplankton community at stations 13, 14, and 16, located in the north of the study area, were the reason for placing them in a separate group (Table 4). Along with aquatic organisms numerous in the northern area, specimens of the southern Bering Sea oceanic grouping of species, *C. cristatus, C. plumchrus, E. bungii, Microcalanus pygmaeus, Metridia pacifica*, and *Oncaea borealis*, as well as neritic *Centropages mcmurrichi*, cirripede larvae, and larval stages of euphosids, were observed in massive numbers only at these stations.

At all stations of the northern area, *Pseudocalanus minutus* and *Oithona similis* were present in large quantities in the plankton. The numbers of *P. minutus* remained at the same level as in the surface levels of the deepwater portion of the Bering Sea, whereas the numbers of *Oithona similis* decreased considerably (Table 4).

The population of *Calanus plumchrus* in the northern portion of the area consisted of specimens of copepodite stages III-VI, and, despite differences in extent of the layers considered, the numbers of stage V copepodites

Table 3. *Age structure of densely concentrated copepod species (thousands/m²) in deepwater polygons.*

Stages of development	*Calanus pluchrus* Polygons South	East	West	*Eucalanus bungii* Polygons South	East	West
Nauplii	1.6	2.5	4.4	3.1	8.1	9.2
Copepod						
I	0.3	0.1	0.7	0.5	1.0	3.4
II	0.4	0.1	1.1	0.9	1.6	4.9
III	0.3	0.1	0.5	1.2	2.0	2.1
IV	0.3	0.2	1.2	0.8	0.7	0.5
V	2.1	1.4	1.1	0.7	0.2	-
VI	-	-	-	0.3	0.4	-

Table 4. *Average values of numbers (N, in thousands of specimens/m²) and biomass (B, g/m²) of densely concentrating species and groups of species on the northeastern Continental Shelf of the Bering Sea at the 0- to 45-m level.*

No.	Species and groups of species	Station 10, 11, 12, 15, 17, 18, 19 N	B	13,16 N	B
1.	Medusa juv.	15.0	0.1	0.5	0.1
2.	Synchaeta sp.	11.6	0.1	0.2	0.1
3.	Meroplankton	22.6	1.0	55.2	4.6
4.	*Calanus cristatus* cop.	-	-	0.2	2.8
5.	*C. plumchrus* cop.	-	-	3.0	7.4
	adults	-	-	0.1	0.3
6.	*C. glacialis* cop.	3.2	2.5	0.4	0.3
	adults	0.1	0.2	-	-
7.	*Eucalanus bungii* cop.	-	-	1.0	0.9
	adults	-	-	0.3	2.5
8.	*Pseudocalanus minutus* cop.	10.6	0.1	14.4	0.2
	adults	0.8	0.1	2.1	0.2
9.	*Microcalanus pygmaeus* cop.	-	-	3.3	0.1
	adults	-	-	3.0	0.1
10.	*Metridia pacifica* cop.	0.2	0.1	5.3	0.3
	adults	-	-	0.7	0.5
11.	*Oithona similis*	22.0	0.1	23.5	0.2
12.	*Oncaea borealis*	0.9	0.1	47.5	0.3
13.	Cyclopoida nauplii	14.6	0.1	13.1	0.1
14.	Calanoida nauplii	20.2	0.1	54.8	0.2
15.	Euphausiacea larvae	0.1	0.1	7.1	2.5
16.	*Fritillaria borealis*	0.3	0.1	4.5	0.1
17.	*Oikopleura labradoriensis*	5.0	1.9	15.4	2.3

and mature organisms in the shoal were greater than in the deepwater areas of the Bering Sea. On the average, their mean density was 2,380 organisms/m^2. This was also observed in the distribution of *E. bungii* nauplii--12,400 organisms/m^2. Copepodites of this species were represented by stages I-II and V-VI. Younger copepodites exceeded older ones in numbers by nearly a factor of two: 790 and 480 organisms/m^2, respectively.

On the whole, accumulations of *Microcalanus pygmaeus* at stations 13, 14, and 16 were relatively sparse: nearly half the population consisted of females and males (3,000 organisms/m^2), whereas in the surface 200 m layer of the deep-sea areas they were encountered only sporadically.

With the population of *Metrida pacifica*, whose density in the northern portion of the north polygon was more than an order of magnitude higher than in the southern portion, the fraction of mature crustaceans was ten times that at the deep-sea polygons (Table 4).

Such massive penetration of the surface-water fauna of the deepwater areas of the Bering Sea into the shoal northern portion of the northeastern shelf area is due to the Anadyr Current, which removes waters from the central areas along the coast of the Chukot Peninsula through the Bering Straits and into the Chukchi Sea (Stepanova 1937; Aresen'ev 1967).

A species complex consisting of *C. glacialis, Acartia longiremis*, meroplankton organisms, the rotifer *Synchaeta* sp., and juvenile medusae *Aglantha digitale* and *Rathkea octopunctata*, dominated over a large portion of the study area of the shelf zone in the southern portion of the northern region. Altogether in the community, specimens of *C. glacialis* dominated in biomass, and planktonic larvae of benthic animals dominated in numbers.

The largest part of the *C. glacialis* population consisted of the nauplial and younger copepodite stages, but older copepodites surpassed them in biomass.

Vertical Distribution of Mesozooplankton

In the deepwater areas of the Bering Sea, at the south, east, and west polygons, the 0 to 200-m depths studied were subdivided into two layers according to the species structure and numbers of the mesozooplankton: the surface (25-m) layer, corresponding to the water masses of the surface thermal layer (Aresen'ev 1967), with high numbers of *Oithona similis, Oncaea borealis, Pseudocalanus minutus, Calanus plumchrus*, nauplii and younger copepodites of *Eucalanus bungii* and *Metridia pacifica*; and the 45- to 150-(200)-m layer, corresponding to the depths of occurrence of the cold intermediate layer of water masses, with relatively lower numbers of *Oncaea borealis, O. minuta, Microcalanus pygmaeus, Metridia pacifica, Microsetella rosea* and older copepodites of *C. cristatus* and *E. bungii.* The thermocline, located at a depth of 25-45 m, was usually characterized by the highest density of accumulation of both groups of aquatic organisms.

The water temperature in the warm surface layer during the study period ranged from 7 to 10°C. In the 45- to 200-m layer, a drop in temperature to 3-4°C at the south and east polygons and 1-2°C at the west polygon took place. The salinity increased with depth from 32.20-33.08 ppt in the surface layer to 33.20-33.70 ppt at a depth of 200 m.

The vertical distribution of the massive species at the south, east, and west polygons had common features (Table 5). Large filter-feeding copepods, relatively few in number, made up 90% of the biomass of the entire mesozooplankton at some levels.

Calanus cristatus was represented by copepodite stages III-V. Its greatest accumulations were confined to the 45-m level (up to 100 organisms/m^3). On average, its numbers did not exceed 30 organisms/m^3.

The core of the *C. plumchrus* population was located in the 0- to 25-(45)-m layer. Its nauplii favored the 0- to 10-m levels with average numbers up to 360 organisms/m^3. Copepodite stages occurred in numbers of about 100 organisms/m^3. On the whole, older copepodites of *C. plumchrus* surpassed younger stages in numbers and biomass, and their density reached 270 organisms/m^3 (station 1, surface level). Mature specimens occurred sporadically.

The *E. bungii* population in deep-water areas of the Bering Sea had a vertical distribution character that was similar to *C. plumchrus* in many respects. Their quantitative indicators were also similar. However, older copepodites of *E. bungii* occupied a wider range of depths, from 0- to 200 m. This was due to the ability of copepodite stages III-VI to engage in diurnal vertical migrations (Vinogradov 1954; Geynrikh 1957). The largest quantity of small crustaceans was observed at the 25-m level. Stages II and III dominated in numbers.

Massive accumulation of specimens of all age stages of the epipelagic species *P. minutus* was confined to the surface water masses to a depth of 45 m. The number of nauplii at the surface level amounted to an average of about 1,000 organisms/m^3 (maximum of 6,000 organisms/m^3 at station 20), and copepodites numbered 500 organisms/m^3. *Pseudocalanus minutus* represented 6% of the total mass of mesozooplankton (Table 5).

Table 5. *Portion (%) of numbers (N) and biomass (B) of densely concentrating species and groups of species in the total numbers and biomass on average in the north polygon.*

No.	Species and groups of species	Levels (meters) 0		10		25		45		0		100		150		150	
		N	B	N	B	N	B	N	B	N	B	N	B	N	B	N	B
1.	*Calanus cristatus*	-	-	-	-	<1	9	1	73	1	59	1	57	<1	46	<1	22
2.	*Calanus plumchrus*	1	35	<1	31	<1	17	<1	7	<1	5	<1	7	<1	9	<1	5
3.	*Eucalanus bungii*	<1	6	<1	7	1	33	1	11	2	9	1	28	1	30	1	40
4.	*Pseudocalanus minutus*	3	6	1	6	2	3	1	1	1	<1	<1	<1	-	-	-	-
5.	*Microcalanus pygmaeus*	-	-	-	-	<1	<1	5	1	13	2	15	2	11	1	10	1
6.	*Metridia pacifica*	<1	<1	2	6	3	8	2	1	3	1	2	2	2	3	3	11
7.	Calanoida nauplii	12	4	6	2	10	3	16	<1	27	1	27	1	13	<1	10	1
8.	*Oithona similis*	33	20	37	21	38	13	37	2	21	2	13	1	20	1	10	1
9.	*Oncaea borealis*	<1	<1	1	<1	8	3	9	<1	12	<1	15	1	14	1	11	1
10.	*Oncaea minuta*	-	-	-	-	-	-	-	-	-	-	1	<1	7	<1	21	<1
11.	Cyclopoida nauplii	43	12	43	12	29	5	14	<1	6	<1	10	<1	15	<1	9	<1
Total		92	83	90	85	91	94	86	96	86	80	85	99	83	91	75	82

Specimens of the *Microcalanus pygmaeus* population were observed in the thermocline layer and in the intermediate cold waters. The nauplial and copepodite stages had the highest numbers at depths of 25-100 m, with averagesof up to 200 and 440 organisms/m^3, respectively. Mature organisms were found in the deepwater part of the Bering Sea in small numbers only at the southern polygon in the 150 to 200-m layer. The mean numbers of *M. pygmaeus* amounted to 15% of the total number of animals in the intermediate cold layer.

Metridia pacifica was the most numerous of the calanids in the deepwater areas of the Bering Sea (including the nauplial stages). Its specimens were recorded at all the depths studied. The greatest accumulations were noted in the thermocline layer, where they represented 8% of the total biomass at the 25-m level; the mean number of nauplii was 3,200 organisms/m^3 and of copepodites was 2,600 organisms/m^3. Female and male *M. pacifica*, which migrate actively in the course of a day, were observed at all the levels in unit amounts.

The main fraction of the total numbers of mesozooplankton in the surface layers of the 200-m layer consisted of small cyclopoids--*Oithona similis* and *Oncaea borealis* (Table 5)--and their nauplii. Specimens of *Oithona similis* favored the warm surface layer, where its mean numbers reached 13,000 organisms/m^3, and *Oncaea borealis* favored the thermocline layer and the intermediate cold layer in amounts of up to 4,300 organisms/m^3. The population of *O. minuta* was confined to the lower layers of the intermediate cold layer, where its density amounted to 21% of the mesozooplankton numbers.

Among other groups of animals, the most important ones in the plankton were foraminifers, the pteropod *Limacina helicina*, euphosid furcilia, amphipods *Parathemisto pacifica*, small specimens of the chaetognath *Parasagitta elegans*, and appendicularians *Fritillaria borealis*. Specimens of these species inhabited primarily the 45-m surface water layer and during the study period did not play a significant role in the distribution of the quantitative indicators of the state of the mesozooplankton community in the surface waters over deepwater areas of the Bering Sea.

In the northern shelf study area, the nature of the distribution of large numbers of species of aquatic organisms over the levels was not as well defined as in the deepwater areas because of the shallow depths at the stations (up to 100 m). However, the contrasting temperature conditions in the surface and bottom water masses unquestionably influenced the vertical distribution of plankton.

The surface waters (0- to 15-m layer) of this area were heated to 6-8°C: below them was a cold water mass whose temperature in the near-bottom levels dropped to -1.7°C. An exception was the shallowest northern station 14, where the water temperature at the surface reached only 2°C and dropped to 0°C at the bottom. The water salinity in the study area ranged from 30.3 ppt on the surface to 33.0 ppt in the lower levels.

Juvenile medusae, mainly *Aglantha digitale* and *Rathkea octopunctata*, with mean numbers up to 820 organisms/m^3, scanty neritic copepods *Acartia longiremis* and *Centropages mcmurrichi*, and larval stages of euphosids exclusively inhabited the 0- to 10-m warm surface layer. Pelagic nemerteans, found in amounts of about 60 organisms/m^3, favored the cool bottom waters. In most cases, meroplankton organisms avoided the surface level, exhibiting a relatively uniform distribution in the remaining water mass. Polychaete larvae, which were the most massive of this group, amounted to an average of 31% of the total numbers of the zooplankton (Table 6).

The representative of the north Bering Sea grouping *C. glacialis* dominated in biomass at a majority of the stations, and its fraction in the mesozooplankton at the surface level was 44% of the total mass. Nauplii of *Calanus glacialis*, like those of most other calanids, were

observed at all the studied levels in approximately the same quantity. Younger copepodites of *Calanus*, of stages I-III, were confined to the lower 25- to 45-m layer and exhibited a mean number of 70 organisms/m^3; older ones were confined to the warm surface layer, and their mean number was 20 organisms/m^3.

The number of *Pseudocalanus minutus*, which amounted to up to 10% of the total number, was of the same order of magnitude as in the surface layers of the deepwater part of the Bering Sea and was distributed at depths without distinct peaks. However, the density of the *Oithona similis* and *Oncaea borealis* populations decreased by an order of magnitude while retaining the structure of the vertical distribution.

The majority of the southern Bering Sea oceanic species observed at the northern stations of the polygon were concentrated in the 10- to 45-m layer. An exception was copepodites of *Calanus plumchrus* of stages III-IV, found only at the 0- and 10-m levels, while its older copepodite stages formed maximum accumulations at a depth of 45 m with mean numbers of 80 organisms/m^3.

Distribution of Mesozooplankton Total Numbers and Biomass

The main features of the vertical distribution of mesozooplankton total numbers and biomass are shown in Figs. 1-4. The maximum accumulation density of aquatic organisms in the deepwater portion of the Bering Sea is confined to the 25-m surface layer. The quantity of animals at these depths, mainly small cyclopoids and copepod nauplii, usually exceeded 10,000 organisms/m^3. The highest numbers of mesozooplankton were observed at station 25: 63,000 organisms/m^3. As the depth increases, the density of the community decreases, sharply at first, at the 45-m level by approximately an order of magnitude, then more gradually. The smallest numbers of aquatic organisms were found in samples from the 70- to 150-m intermediate cold layer, up to 100 organisms/m^3.

As the depths at the stations decrease and the shelf is reached, the structure of the

Table 6. *Portion (%) of numbers (N) and biomass (B) of densely concentrating species and groups of species in the total numbers and biomass on average in the north polygon.*

No.	Species and groups of species	Levels (meters) 0 N	0 B	10 N	10 B	25 N	25 B	45 N	45 B
1.	Polychaeta larvae	3	1	16	3	10	9	31	8
2.	*Calanus glacialis*	1	44	<1	15	1	9	3	9
3.	*Pseudocalanus minutus*	10	8	2	1	9	2	10	3
4.	Calanoida nauplii	16	2	8	<1	17	1	16	<1
5.	*Oithona similis*	20	7	11	1	8	1	2	1
6.	*Oncaea borealis*	<1	<1	7	1	13	1	8	1
7.	Cyclopoida nauplii	19	3	7	<1	4	<1	1	1
8.	*Ophiura* sp. juv.	-	-	<1	1	2	17	3	22
9.	Appendicularia	2	4	8	23	3	11	1	4
	Total	71	70	61	50	66	52	75	47

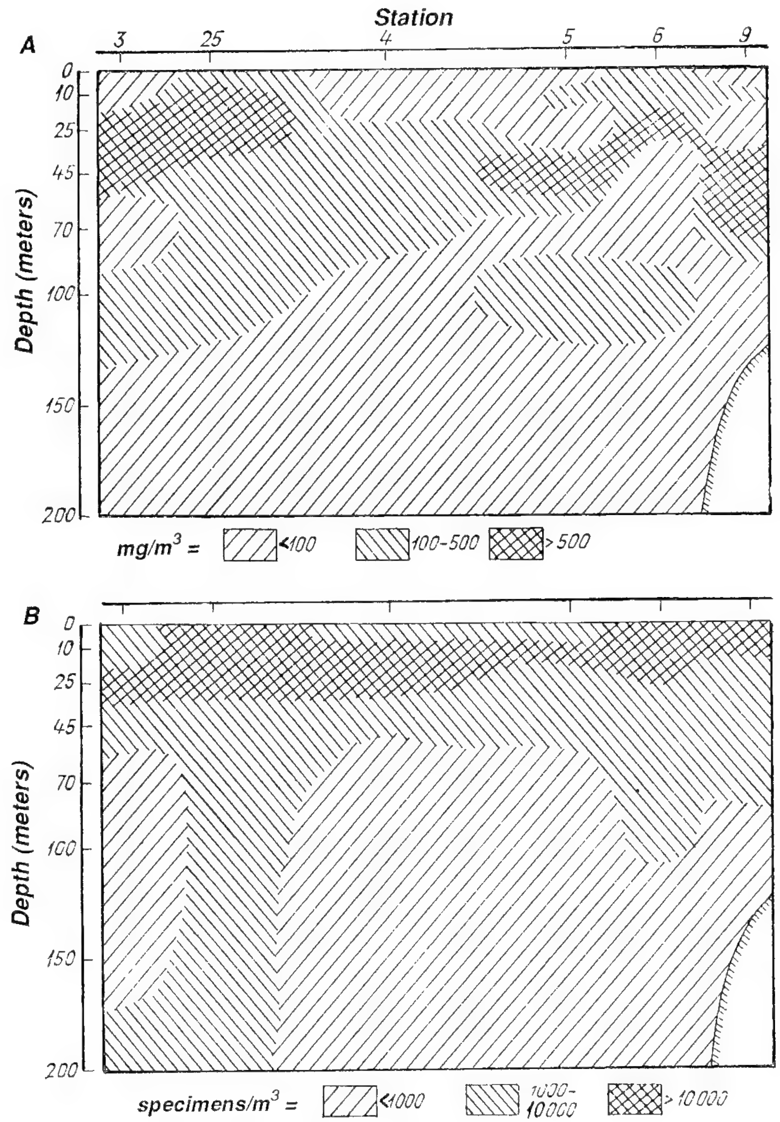

Fig. 1. Vertical distribution of total biomass (A) and numbers (B) of mesozooplankton in the southeast section of the Bering Sea.

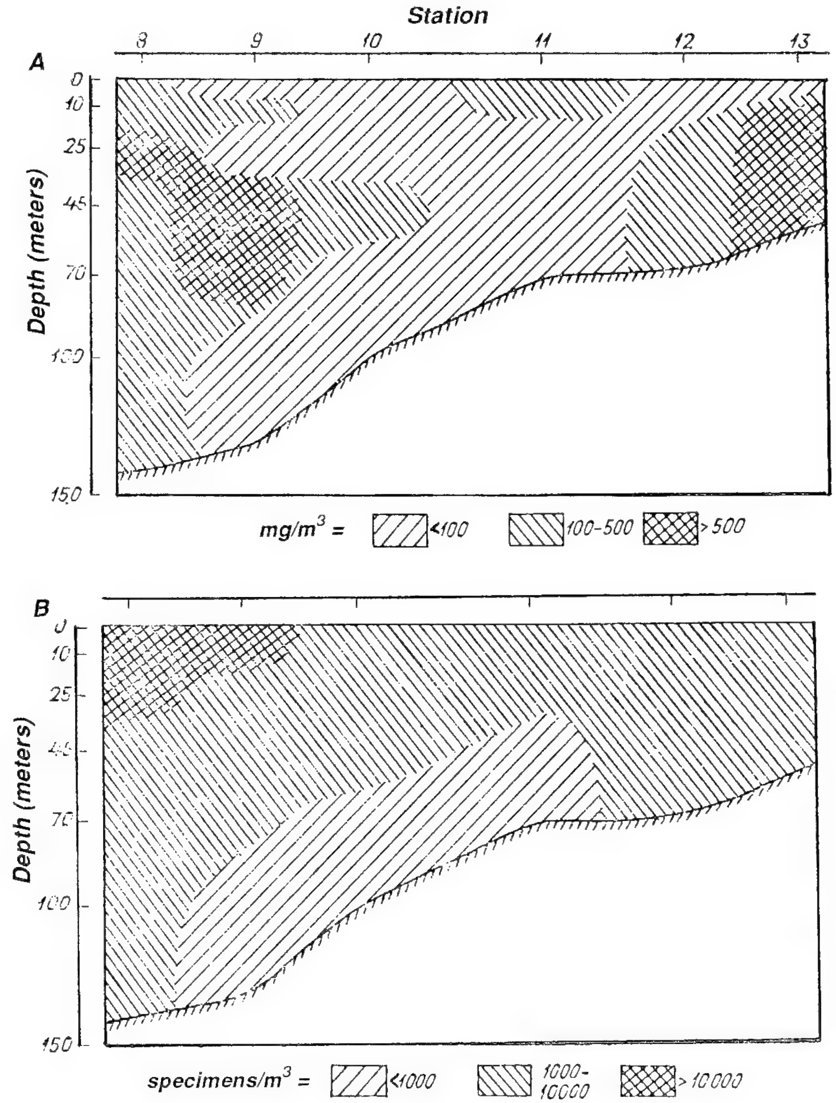

Fig. 2. Distribution of total biomass (A) and numbers (B) of mesozooplankton in the northeast section of the Bering Sea.

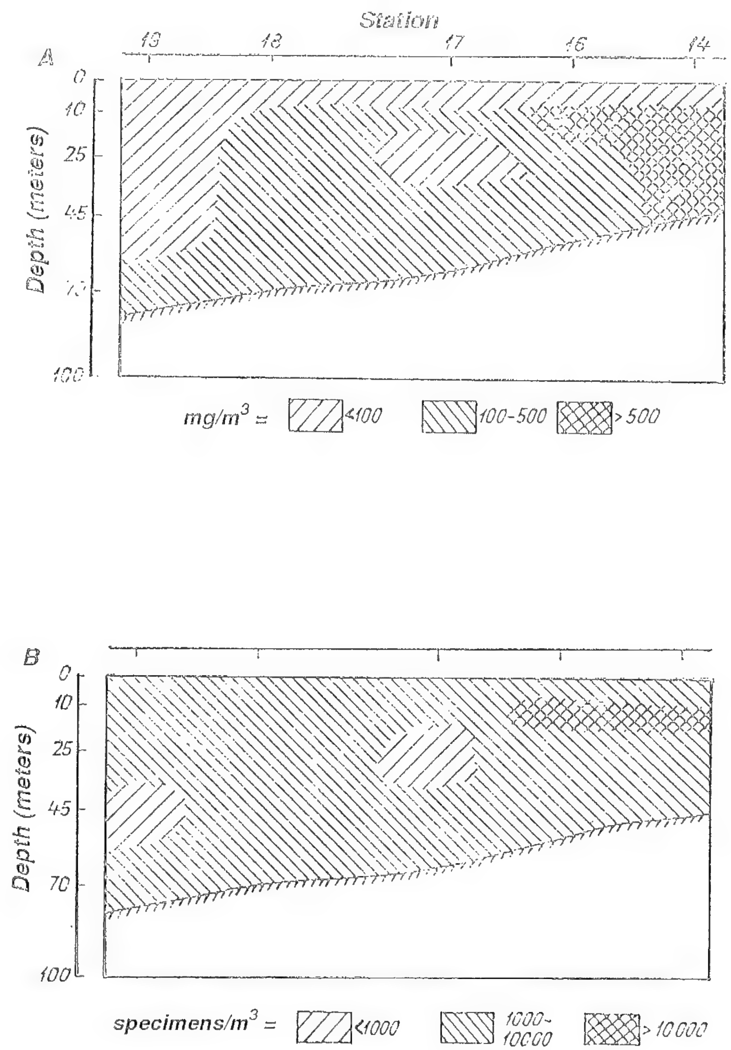

Fig. 3. Distribution of total biomass (A) and numbers (B) of mesozooplankton in the northwest section of the Bering Sea.

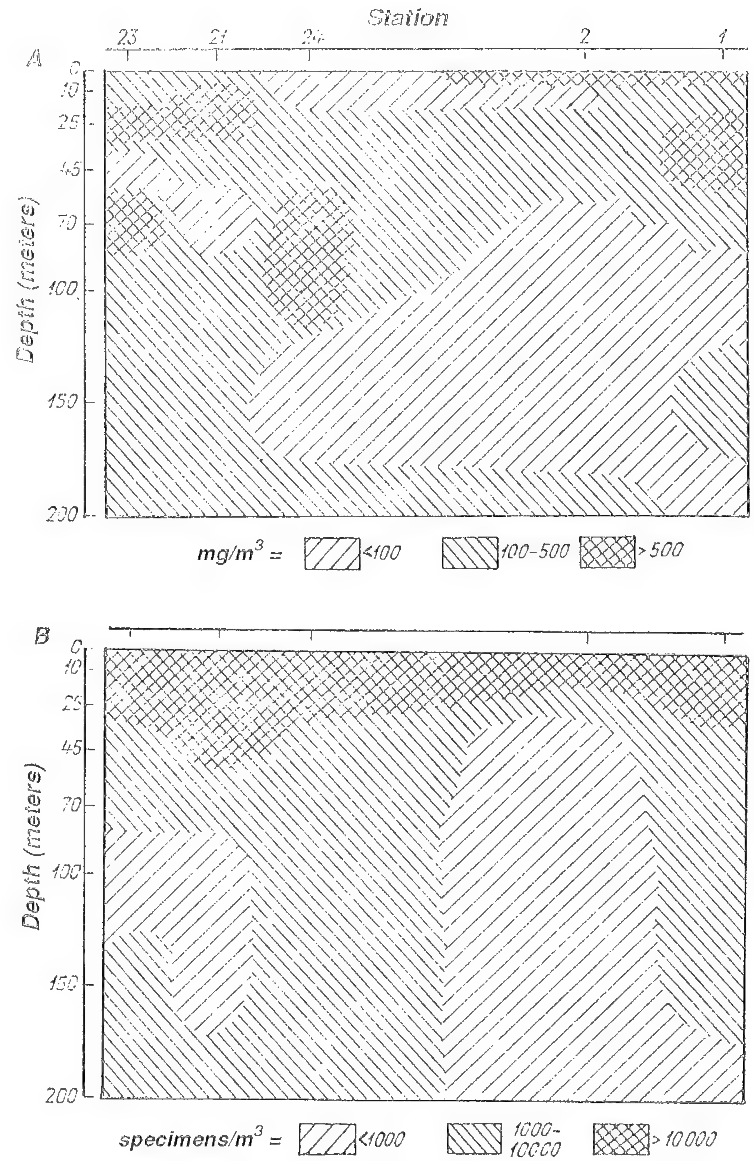

Fig. 4. Distribution of total biomass (A) and numbers (B) of mesozooplankton in the southwest section of the Bering Sea.

vertical distribution of the mesozooplankton total numbers assumes a uniform character (east - north section, Fig. 2). At stations in the northern study area, the quantity of organisms as a whole changes insignificantly--from 2,000 to 9,000 organisms/m^3. The total numbers of mesozooplankton exceeded 10,000 organisms/m^3 (16,000 organisms/m^3, station 16) only at stations 14 and 16 at the 10-m level.

The distribution characteristics of the total biomass are determined to a considerable degree by the distribution of the specimens of the large filterer copepods. The highest values of total biomass were recorded at the depths of accumulation of the copepodite stages. In the area of the south polygon in the richest 0- to 45-m layer, the average value was 535 mg/m^3, and at the east and west polygons in the 10- to 70-m layer, about 450 mg/m^3.

On the shelf of the northeastern portion of the Bering Sea, no distinct pattern was found in the distribution of the mesozooplankton biomass with depth.

The biomass levels at individual stations of the area showed significant differences. While at stations 13, 14, and 16 of the north polygon the biomass in the 10- to 45-m layer ranged from 360 to 1,230 mg/m^3 with an average of 624 mg/m^3, at the remaining stations of the polygon it ranged from 1 to 320 mg/m^3, with an average of 133 mg/m^3. The lowest levels were observed at the surface. As in the deepwater part of the Bering Sea, accumulation of large crustaceans of the oceanic species complex determined the big values of the biomass.

The general pattern of distribution of total numbers and biomass over the water area of the Bering Sea is shown in Fig. 5, which gives their horizontal distribution in the 0- to 100-m layer at deep-water stations and in the 0- to 45-m layer in the shoal shelf area studied. The numbers in the southern, eastern, and western Bering Sea ranged from 310,000 organisms/m^2 (at station 2) to 1,810,000 organisms/m^2 (at station 25), and the biomass ranged from 13 g/m^2 (at station 2) to 53 g/m^2 (at station 1). The mean values of the numbers and biomass under a square meter did not show any appreciable differences (Table 7).

In the region of the Continental Shelf, the maximum numbers (330,000 organisms/m^2) and biomass (27 g/m^2) were recorded in its northern portion at station 16. Similar levels of these characteristics were also noted at stations 13 and 14. On average, the total numbers here reached 318,000 organisms/m^2, and the total biomass was 23 g/m^2. At stations of the shelf zone located further south, the mean values did not exceed 174,000 organisms/m^2 and 6 g/m^2.

Discussion and Conclusion

Comparing the state of the mesozooplankton community of the Bering Sea at the west, south, and east polygons for July 1984 with the data obtained in June 1981 (Izrael, in press), and with the results of other studies (Stepanova 1937; Vinogradov 1956; Mednikov 1957; Meshcheryakova 1964a,b; Motoda and Minoda 1974; Kun 1975; Izrael 1983), we should note first of all that the composition of the dominant group of species of aquatic organisms did not change significantly. Representatives of the south Bering Sea oceanic grouping and the eurybiotic species *Pseudocalanus minutus* and *Oithona similis* dominated in the plankton. Differences in the state of the community amounted mainly to seasonal changes in the plankton, manifested in the degree of development of the neritic complex, in the dynamics of the age structure of the populations, and in the relationship of the quantitative characteristics of the mesozooplankton.

According to the data in Vinogradov (1956), the range of the neritic species grouping expands in the summer, going beyond the confines of coastal shoal and shelf areas of the sea. This trend in the development of the neritic complex was noted in the south polygon, where the sampling was done at the beginning and end of July 1984. Although the neritic

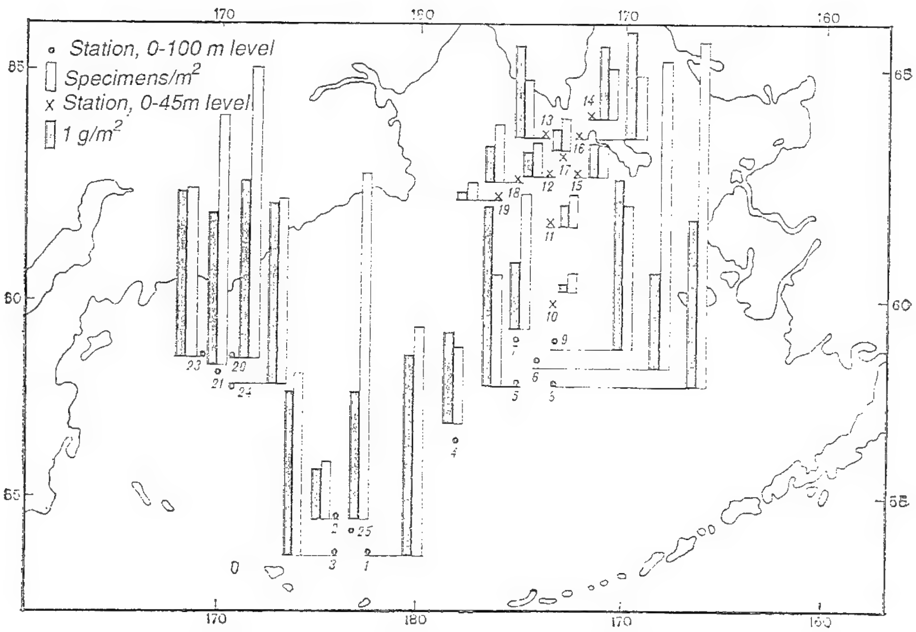

Fig. 5. Distribution of total numbers and biomass of mesozooplankton in the Bering Sea in July 1984.

Table 7. *Average values of the total numbers (in thousands of specimens/m²) and biomass (g/m²) in the 0- to 100-m level.*

Index	Polygons West	East	South
Total number	1,171	1,032	1,067
Total biomass	44	35	35

component was practically absent from the community during the first few days of the month, typical representatives of this grouping were observed in the composition of the plankton in the mass at the end of the study period. However, the opposite was observed in the west polygon. In June 1981, the spring mesozooplankton community in the western study region was characterized by a high density of accumulations of meroplankton neritic organisms, and in the summertime, July 1984, their abundance level was much lower and did not exceed the mean level at other deep-sea polygons.

The change in age structure of the populations of the species dominant in the deepwater region of the Bering Sea is due to the process of maturation of the mesozooplankton community in the summer period (Vinogradov 1956; Geynrikh 1957, 1959). In June 1981, nauplial and younger copepodite stages of development of *Calanus plumchrus*, *Eucalanus bungii*, *Mehidia pacifica*, and other massive species of copepods predominated in the surface levels, and in July 1984 their fraction in the populations decreased considerably, and older copepodites of these species became more numerous. Nauplii and

younger calyptopes of euphosids were replaced by older calyptopes and furcilia.

Owing to the decrease in the numbers of younger age groups in the plankton in July, the level of mesozooplankton total numbers dropped by a factor of 1.5–2 in comparison with June. In the western Bering Sea in June, the mean biomass of mesozooplankton obtained by Vinogradov in the richest 10- to 50-m layer amounted to 882 mg/m^3 (Vinogradov 1956). The June 1984 biomass was close to the level of the total biomass in the 10- to 45-m layer in June 1981 (725 mg/m^3) and almost twice as high as the value of the indicator in July 1984 (450 mg/m^3). These relationships are consistent with Vinogradov's statement that the mean zooplankton biomass in the surface waters is highest in May-June and approximately twice as high as in summer.

For the area where the depths increase rapidly, approximately at the location of the east polygon, the average value of zooplankton biomass is in excess of 500 mg/m^3 (Meshcheryakov 1970a), which corresponds to the level recorded in the surface 100-m layer, in June 1981, and is higher than the July 1984 average of 355 mg/m^3.

Mesozooplankton biomass values calculated under a square meter in the 0- to 100-m layer from our data for June and July at deep-sea polygons ranged, on the average, from 37 to 35 mg/m^2 at the south polygon, from 55 to 35 mg/m^2 at the east polygon, and from 40 to 44 mg/m^2 at the western polygon (Table 8). They exceed somewhat the long-term average levels—28.4 g/m^2 in the southern area—in the 0- to 80-m layer, obtained as a result of a 15-year study of the summer zooplankton of the Bering Sea by Japanese investigators (Motoda and Minoda 1974).

The species composition of the mesozooplankton of the northern area of the Bering Sea was quite different. In the waters of this area, mixing of three faunistic groupings of zooplankton—southern Bering Sea oceanic, northern Bering Sea, and neritic groupings (Stepanova 1937; Vinogradov 1956)—takes place. In June 1981, representatives of only two complexes, oceanic and neritic, were found. *Calanus glacialis*, characteristic of the northern Bering Sea groupings (Vinogradov 1956; Kun 1975), was represented by only isolated specimens of mature females. Apparently, because of its absence from the plankton, the antagonist of this species, *C. plumchrus* (Kun 1975), became widespread in the shoal. The bulk of the zooplankton consisted of specimens of *P. minutus*. In July 1984, the structure of the mesozooplankton community at the polygon changed somewhat. The composition of the

Table 8. *Average values of the total numbers (N, in thousands of specimens/m^2) and biomass (B, mg/m^2) of mesozooplankton in the Bering Sea according to research materials in June 1981 and July 1984.*

Region (level)	1981		1984	
	N	B	N	B
South polygon (0-100 m)	2,468	37	1,067	35
East polygon (0-100 m)	1,558	55	1,032	35
West polygon (0-100 m)	1,555	40	1,171	44
Northern north polygon (0-45 m)	1,452	12	318	23
Southern north polygon (0-45 m)	1,297	10	174	6

community in the northern portion of the polygon included representatives of all three groupings, and in its southern portion, there were actually only two, the neritic and northern Bering Sea groupings, with *C. glacialis* specimens predominating in biomass.

During the 1981 and 1984 study periods, the high density of the southern Bering Sea oceanic species in the northern portion of the polygon was maintained owing to the transport by the Anadyr Current of nutrient-rich waters from the Bering Sea slope across the shelf (Sambrotto et al. 1984). Mesozooplankton numbers and biomass in this area were 12 g/m^2 in June 1981 and 23 g/m^2 in July 1984 (Table 8). While the July biomass doubled in comparison to the June biomass, the total numbers decreased by a factor of 4.5, from 1,452,000 to 318,000 organisms/m^2.

In the southern portion of the north polygon in July, the numbers and biomass were lower than in June by factors of 7.5 and 2, respectively.

The biomass in the northern portion of the north polygon, recorded in July 1984, was closest in value to the average long-term value of 29.9 g/m^2 in the 0- to 60-m layer calculated for this area by Japanese investigators (Motoda and Minoda 1974).

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ZOONEUSTON OF THE BERING SEA

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The study of the population of the Bering Sea neuston is of interest from several points of view. First, it makes it possible to obtain new data on the neuston of the high-latitude region of the Pacific Ocean, which has been little studied in this respect, with the exception of bacterioneuston (Tsyban et al. 1985). Second, the Bering Sea is one of the background regions of the World Ocean (Izrael 1983), and hence, its neuston has undergone little change under action of anthropogenic influences, this being very characteristic of many other marine areas today. Third, if such influences have already been observed somewhere in this sea, then it is the neuston, because of its location near the surface and its age composition (predominance of early stages of ontogeny over adult individuals) that should react to these influences most visibly (Zaitsev 1985). On the basis of the general principles of development of marine neuston (Zaitsev 1970a, b), the structure of the near-surface pelagic community in the Bering Sea cannot be identical to that in seas of the temperate and tropical zones. Low values of water temperature, formation of ice over 80%-90% of the surface of the water area during a long winter season, and other natural factors do not permit the development of such euneustonic forms as Pontellidae, Holobatidae, and many others, which in warmer waters populate the neustal year-round. In the Bering Sea, only temporary forms of zooneuston, capable of developing during the short period of the hydrologic summer, can become fairly widespread. They include larvae of various bottom-dwelling animals (mollusks, worms, crustaceans, echinoderms, etc.), as well as circadian migrants from the benthos (benthoneuston) and plankton of the water mass (planktoneuston), which form accumulations at the surface of the pelagic zone during the nighttime.

The extensive shelf in the northeastern half of the Bering Sea and considerable depths in the southwestern portion ensure the conditions for the existence on the Continental Shelf of a bottom fauna with the dominance of bivalve mollusks, echinoderms, and polychaetes, and in the epipelagic region of the deepwater portion of the sea—a rich zooplankton, consisting primarily of crustaceans (Zenkevich 1963). All tend to temporarily exist as neuston.

The first studies of the neuston of the Bering Sea and adjacent waters were carried out in the summer months of 1962 (Chebanov 1965; Zaitsev 1970a) by means of a PNW-2 two-walled plankton-neuston net (Zaitsev 1962, 1970a). The only representative of the warmwater family of Pontellidae, *Epilabidocera amphitrites*, was found in the amount of a few specimens at three stations at a distance of 10-20 miles from Cape Lopatka. In the 0- to 5-cm biotope of the Bering Sea as such, accumulations were formed by juvenile squid 15-20 mm long (primarily, *Ommatostrephes sloanei pacificus*), *Calanus plumchrus* (= *C. tonsus*), *Calanus cristatus*, crab megalopses, amphipods (for example, *Parhyale zibellina*), hyperiids (particularly *Parathemisto japonica*), euphausids (*Thysanoessa inermis, Thysanoessa raschii*, etc.) and other invertebrates, as well as saury larvae (*Gololabis saira*). Calanids, amphipods,

hyperiids, and euphausids appeared in the neustal during the nighttime. Quantitatively, amphipods (particularly, hyperiids) and calanids were dominant.

In July 1984, scientists aboard the RV *Akademik Korolev* carried out a collection of neuston at four polygons (frontispiece) located in different water areas of the Bering Sea (i.e., on the shelf, continental slope, and deepwater region and encompassing northern and western biogeographical areas (Kun 1975)).

The gear consisted of a PNS-2 two-walled net, by means of which a simultaneous collection was carried out in the top layers of the pelagic zone (i.e., the neustal (0-5 cm) and subneustal (5-25 cm)). The net extended over a distance of 45-50 m. The mesh size was 135 μm, and the length of the filtering part was 1.8 m. The working area of the opening of the upper net was 300/cm^2, and that of the lower net, 1200 cm^2. The average drift velocity of the net was 0.24 m/sec (limits: 0.07-0.41 m/sec). The average volume of water filtered by the upper net was 2.65 m^3 (limits: 1.62-5.05 m^3), and that of the water filtered by the lower net, 10.62 m^3 (limits: 6.7 m^3 - 20.22 m^3). The net was hauled in at rate of 25 cm/sec[1].

At the 26 stations of the four polygons, a total of 58 samples were obtained: 26 in each of the microlevels studied. The samples were processed in the ship's laboratory. The correlation coefficients between the individual biotic and abiotic parameters were calculated with an ES-1022 computer.

Analysis of the samples showed the following results. The animal population of the neustal and subneustal of the Bering Sea during the work of the expedition was represented by a wide variety of species. Present in the samples were protozoans (foraminifers, tintinnians), *Aglantha digitalis*, pteropods, arrowworms, ctenophores, copepods (the most numerous group), hyperiids, amphipods, euphausids, larvae of bottom-dwelling invertebrates (bivalves and gastropods, cirripedes, decapods, brittle stars, sea urchins), larvae of cephalopods and polychaetes, appendicularians, and fish roe, larvae, and fingerlings.

In 84% of the cases, accumulation of organisms in the neustal was reliably observed. Thus, the mean total numbers of aquatic organisms in the 0.5-cm layer for the entire sea were 20.7 x 10^3 organisms/m^3, and in the 5- to 25-cm layer, only 11.2 x 10^3 organisms/m^3 (Table 1). At individual stations, the total numbers of aquatic organisms in the neuston were 10-15 times as high as in the subneuston. Even more appreciable was the difference between the two microlevels studied when individual species or stages of ontogenetic development were compared. The relationship of the individuals in the neuston and subneuston according to individual taxons and stages of ontogenetic development is shown in Table 2. In the samples, there was a quantitative dominance of copepods (Table 3), among which are distinguished the following three species: *Oithona similis, Pseudocalanus minutus* (= *P. elongatus*), and *Acartia longiremis* (Table 4). An idea of the age structure of the populations of the leading species in the neustal layer is given in Table 5. It is evident that a preponderant role is played here by the early stages of development. The work of Minoda (1972) and Motoda and Minoda (1974) showed that the first two species in the Bering Sea are distributed throughout the water mass, and the third species is confined to the epipelagic zone. Nevertheless, they all behave as obvious neustophiles, and in the PNS-2 samples, from 60% to 88% of the individuals are seen in the 0- to 5-cm layer. Other less massive species of animals also behave as typical neustophiles in the majority of cases, at least in the early stages of development. Thus, in the 0- to 5-cm layer, 88% of *Eucalanus bungii* nauplii, 91% of *Centropages mcmurrichi* adults, 71% of cirripede nauplii, 79% of larvae of the pelagic polychaete tomopteris, 60% of crab megalopses, 68% of *Calanus plumchrus* nauplii, etc., were observed. On the other hand, organisms are distinguished which did not manifest this tendency, for example, *Clione limacina*,

Table 1. *Average number (specimens/m^3) of organisms in neustals and subneustals in the Bering Sea in July 1984.*

Section	Station no.		Microlayers, cm 0	5-25
South polygon	Station	1	41,113	20,123
		2	31,827	11,278
		3	44,369	30,151
		25	31,253	35,452
		26	20,853	14,046
Average for the polygon			33,883	22,210
South-east transect	Station	4	53,022	26,807
East polygon		5	39,141	25,607
		6	39,650	26,340
		7	4,069	7,430
		8	23,312	16,554
		9	23,312	17,002
Average for the polygon			26,025	18,587
East-north transect	Station	10	2,390	1,488
		11	5,223	1,508
Average for the transect			3,806	1,498
North polygon	Station	12	2,638	814
		13	3,801	1,992
		15	3,987	993
		16	3,136	735
		17	4,544	2,562
Average for the polygon			3,621	1,419
North-west transect	Station	14	5,229	1,123
		18	18,605	1,172
		19	7,612	2,097
Average for the transect			10,482	1,464
West polygon	Station	20	12,728	7,515
		21	6,927	3,762
		22	40,121	21,580
		23	4,003	5,821
		24	8,867	8,963
Average for polygon			14,529	9,528
Average for the sea			20,767	11,645

Table 2. *Composition and average number of organisms in neustals and subneustals of the Bering Sea in July 1984.*

Organisms	Microlevels (cm) 0-5	5-25	Ratio of amount (in %) to microlayer
Foraminifera			
Globegerina bulloides	167	94	64:36
Tintinnoinea	400	397	50:50
Hydromedusae			
Aegina rosea	0	0.007	0:100
Aglantha digitale	54	28	68:34
Coryne princeps	0.04	0.01	80:20
Coryne tubulosa	0.2	0	100:0
Corymorpha sp.	0.05	0.03	63:37
Rathkea octopunctata	13	6	68:32
Pandea conica	4	0	100:0
Hydromedusae sp. sp.	25	1	96:4
Total Hydromedusae	96	35	74:26
Pteropodae			
Clione limacina	2	3	40:60
Limacina helicina	38	16	70:30
Total Pteropodae	40	19	68:32
Chaetognatha	64	19	77:23
Ctenophora	0.01	0.04	20:80
Copepoda			
Oithona similis, juvenis	8,131	5,404	60:40
Oithona similis, adultis	2,578	1,707	60:40
Total *Oithona*	10,709	7,111	60:40
Calanus plumchrus, nauplii	66	31	68:32
Calanus plumchrus, juvenis	25	20	55:45
Calanus plumchrus, adultis	0	0.4	0:100
Total *Calanus*	91	51.4	64:36
Pseudocalanus minutus, nauplii	1,872	801	70:30
Pseudocalanus minutus, juvenis	1,164	584	66:34
Pseudocalanus minutus, adultis	940	68	88:12
Total *Pseudocalanus*	3,976	1,453	71:29
Eucalanus bungii, nauplii	619	86	88:12
Eucalanus bungii, juvenis	43	22	66:34
Eucalanus bungii, adultis	0.04	0	100:0
Total *E. bungii*	662.04	108	86:14
Acartia longiremis, nauplii	2,131	1,429	59:41
Acartia longiremis, juvenis	16	11	59:41
Acartia longiremis, adultis	27	13	68:32
Total *A. longiremis*	2,174	1,453	60:40

Table 2. *Continued.*

Organisms	Microlevels (cm) 0-5	Microlevels (cm) 5-25	Ratio of amount (in %) to microlayer
Acartia tumida, adultis	0.1	0	100:0
Eurytemora americana, juvenis	0.3	0	100:0
Eurytemora americana, adultis	0.7	0.1	70:30
Total *E. americana*	1.0	0.1	92:8
Epilabidocera amphitrites, nauplii	0.7	0	100:0
Centropages mcmurrichi, juvenis	0.3	0.07	70:30
Centropages mcmurrichi, adultis	2	0.2	91:9
Total *C. mcmurrichi*	2.3	0.27	89:11
Copepoda sp., ova	246	267	48:52
Copepoda sp., nauplii	226	43	84:16
Total Copepoda	18,088.14	10,487	63:37
Hyperiidae	45	74	38:62
Amphipoda	0.1	0.02	83:17
Euphausiacea	1	0.1	91:9
Bivalvia, larvae	0.04	3	2:98
Cirripedia, larvae	1	0.4	71:29
Polychaeta, larvae	104	28	79:21
Brachyura, larvae	0.23	0.15	60:40
Decapoda, larvae	0	0.004	0:100
Cephalopoda, larvae	0	0.004	0:100
Ophiura, larvae	0.1	0	100:0
Appendicularia	119	87	58:42
Echinodea, larvae	0.4	0.3	57:43
Varia	167	8	99:1
Total number	20,767	11,645	64:36

Table 3. *Number of individual (%) basic taxonomic groups in neustals and subneustals in the Bering Sea in July 1984.*

Groups of organisms	Microlayers, cm	
	0-5	5-25
Copepoda	95	93
Tintinnoinea	2	3.5
Foraminifera	0.9	0.8
Appendicularia	0.6	0.8
Hydromedusae	0.5	0.3
Polychaeta, larvae	0.5	0.2
Chaetognatha	0.3	0.2
Varia	0.2	1.2

Table 4. *Number of individual copepoda (%) in neustals and subneustals in the Bering Sea in July 1984.*

Species	Microlayers, cm	
	0-5	5-25
Oithona similis	61	67.8
Pseudocalanus minutus	20	13.8
Acartia longiremis	12	13.8
Eucalanus bungii bungii	3.7	1.0
Calanus plumchrus	0.6	0.5
Varia	2.7	3

Table 5. *Aging structure (%) of populations of principle species in the neustal layer of the Bering Sea in July 1984.*

Species	Stages of development		
	Nauplii	Copepods	Adult Individuals
Oithona similis[a]	–	76	24
Pseudocalanus minutus	53	33	14
Acartia longiremis	98	0.7	1.3

[a] Nauplii are not totally caught in the net due to the size of the mesh (135 μm).

bivalve larvae and decapod and cephalopod larvae, which in other seas behave as neustophiles. It is possible that this was due to their low numbers in the samples. On the whole, however, an overwhelming majority of the organisms in the 0 to 25-cm layer clearly preferred the neustal. Absolute attachment to this biotope was found in adults of *Acartia tumida, Eurytemora americana* nauplii, brittle star larvae, and *Epilabidocera amphitrites* nauplii (*E. americana*, known in estuaries and widespread in the Okhotsk Sea, along the shores of Woods Hole and in Narragansett Bay, along the Atlantic coast of North America (Brodskiy 1950), was first cited by us for the northern Bering Sea).

The detection in the subneuston of adult specimens (males) of *Calanus plumchrus* (south polygon, station 1) in the daytime in the amount of 10 organisms/m^3 contradicts the statement that they live only below 200 m and never appear at the surface (Motoda and Minoda 1974). This example once again emphasizes the necessity of studying the community of the open-air contour of the pelagic zone, a study that will yield new details of the biology of the inhabitants of the Bering Sea.

Also of interest is the fact that the leading species in the neuston and subneuston of open areas of the Bering Sea were *Oithona, Pseudocalanus*, and *Acartia*. There is evidence in the literature that the 100-m depth contour separates two main zooplankton communities: one in the direction of the sea, dominated by *Calanus plumchrus, Calanus cristatus*, and *Eucalanus bungii*, and the other in the direction of the shore, dominated by *Pseudocalanus* and *Acartia* (Smith and Vidal 1985).

It is interesting to compare the population densities of the leading species in the neuston with those in the water mass (Table 6). The concentration of all three species in the neuston is an order of magnitude higher than in the pelagic zone.

Collections at many-hour station 22 (west polygon) showed that concentration of migrants from lower layers of the pelagic zone, (i.e., adult specimens of certain copepods as well as hydromedusae, chaetognaths, and hyperiids) takes place in the nighttime hours in the 0- to 5-cm layer (Figs. 1 and 2). The circadian rhythms of the organisms of the epipelagic zone play an important role in the life of the neuston and its relationships to other classes of marine communities. Because of circadian rhythms, new generations of eggs and larvae are brought into the surface layer, either on the bodies of migrants (such as microorganisms) or by surface-active substances; at the same time, food items are washed out of this biotope. For example, chaetognaths can sharply reduce the numbers of the small copepods *Pseudocalanus* and *Acartia*, as well as nauplii of other species (Smith and Vidal 1985).

The species composition and numbers of animals at the surface of the Bering Sea were not the same for all the stations and polygons (Table 1, Figs. 3a, b, c, d). The highest density indices of the organisms in the neustal were recorded in the southern portion of the western region (south polygon), and the lowest, in the northern area of the sea (north polygon) (Fig. 4). In addition, foraminifers, tintinnians, hyperiids, decapod larvae, and *Eucalanus bungii* were completely absent from collections in the north. However, Kun (1975) noted that this region was characterized by the presence of a wide variety of protozoan species, mainly representatives of the Tintinnoinea family. At the same time, there was an increase in the numbers of polychaete larvae, whose density sometimes amounted to 2,000 organisms/m^3, and also an increase in appendicularians.

The trophic relations in the neuston, just as in the pelagic zone, are important for understanding the functioning of the ecosystem. Usually, the plankton community of the phytoplankton-rich upper euphotic zone is characterized by the dominance of phytophage filterers (Parin and Timonin 1977).

On the basis of our own and reported data, we attempted to determine the trophic

Table 6. *Average number (specimen/m^3) of separate taxa in pelagic zones and neustals in the Bering Sea in the summer season. (Data from Shaginian 1983 and Smith and Vidal 1985.)*

Taxa	Pelagic zone				Neustal
	June	August	June	August	(0 - 5 cm)
	(0-100 m)		(0-80 m)		
Acartia	–	–	37.4	88.3	2,174
Pseudocalanus	278	363	211.8	333.9	3,526
Oithona	793	2,147	205.8	219.8	10,700

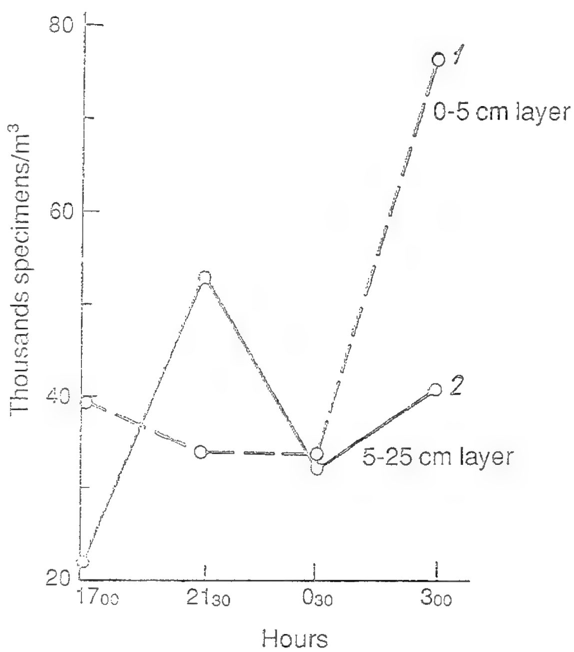

Fig. 1. Dynamics of the total number of organisms in neustal and subneustal of the Bering Sea at Station 22 (west polygon) sampled over the course of many hours 21-22 June 1984.

structure of the inhabitants of the neustal. Although the food relations of neustons and neustophytes are very complex, it was possible to distinguish three trophic groups. The first group is composed of nanophages–consumers of the smallest inhabitants of the neuston: foraminifers, tintinnians, appendicularians, pteropods, nauplii, and copepodite stages I-III of copepods. The second group consists of euryphages, the feeding range of which includes different-sized organisms of both plant and animal origin. These are copepodite stages IV-V of copepod development, as well as adult specimens. Finally, the third trophic group is composed of predators, such as chaetognaths, hyperiids, amphipods, hydromedusae, and larvae of polychaetes, crabs, and other decapods. The main group is composed of euryphages, followed in decreasing order by nanophages and predators. The numerical ratio of euryphages, nanophages, and predators is close to 32:14:1. Such a trophic structure indicates a balance of the ecosystem of the surface biotope of the pelagic zone of the Bering Sea.

There are indications (Smith and Vidal 1984) that the main factors determining the structure of the zooplankton community of Bering Sea shelf waters are the frontal nature of the salinity distribution and the absence of advection. Temperature has an insignificant effect on the numbers of copepods on the outer side of the shelf and on the slope. At the same time, the numbers of copepods in the

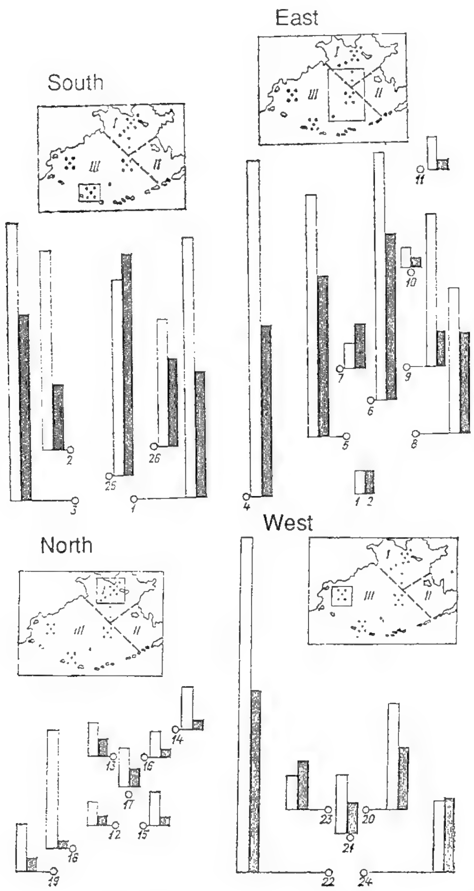

Fig. 2. Dynamics of number of several organisms in the neustal and subneustal of the Bering Sea at a station sampled over the course of many hours 21-22 June 1984.

middle of the shelf depend to some extent on the temperature changes, and the influence on the development of the populations of small-sized species, predominately *Pseudocalanus* and *Oithona*.

During our studies, the water temperature at the surface was in the range 2.01-9.65°C, and the salinity was 30.31%-33.08%. No relationship was observed between the temperature and the numbers of the organisms in the neustal layer (Table 7). A direct relationship was observed between the total numbers of the organisms, and also the numbers of individual taxons in the neustal and subneustal layer, and the salinity. A direct correlation was established between the total numbers of the organisms and the numbers of individual taxa in the neustal layer and the subneustal, and the content of inorganic compounds of nitrogen, phosphorus, and silicon (Table 7). It is well known that plankton animals feeding on diatomaceous algae can excrete inorganic compounds into the water in amounts that often surpass their body content (Harvey 1948; Pomeroy et al. 1963; Johannes 1964; Butler et al. n.d.). Thus, *Calanus* returns to seawater over 80% of the phosphorus contained in food phytoplankton (17.2% is consumed in growth, 23.0% is excreted with fecal matter, and 59.8% is excreted in the composition of soluble compounds) (Pomeroy et al. 1963). Nitrogen, which a small crustacean receives with food, is expended as follows: 26.8% is used in growth, 37.5% is excreted with fecal matter, and 35.7% is excreted in the form of soluble compounds (Pomeroy et al. 1963). The cycle of changes undergone by nitrogen-containing compounds is considerably more complex than the cycle of phosphorus compounds, owing to the variety of the forms of nitrogen and its transformation in the sea. Marine animals excrete nitrogen primarily in the form of ammonia, urea, uric acid, and amino acids (Harvey 1948). The transformation of ammonia into nitrites and nitrates can take place in any medium as a result of a series of reversible reactions. Ammonia is oxidized mainly by bacteria on the bodies of plankton organisms and detritus (Parsons et al. 1982). Thus a part of the phosphorus and nitrogen contained in plant cells is directly regenerated. Like nitrogen and phosphorus, silicon enters the marine environment by direct regeneration.

Thus, on the basis of the above, it may be assumed that the direct relationship between the numbers of organisms at the surface of the Bering Sea and the content of dissolved organic compounds is explained to some extent by the process of direct regeneration of these compounds. On the other hand, the presence of an inverse correlation between the content of inorganic compounds of nitrogen, phosphorus

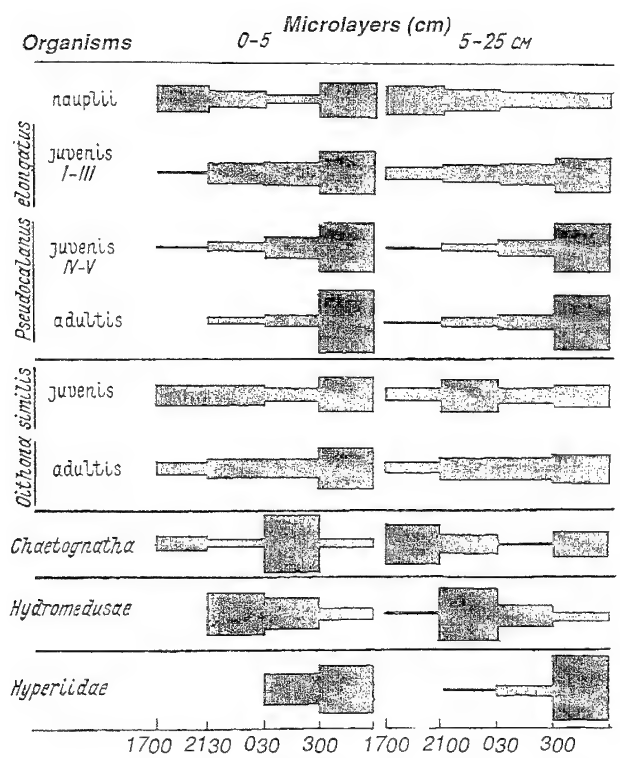

Fig. 3. Number of organisms ($N=10^4$ specimens/m^3) in the neustal and subneustal of the Bering Sea in July 1984.

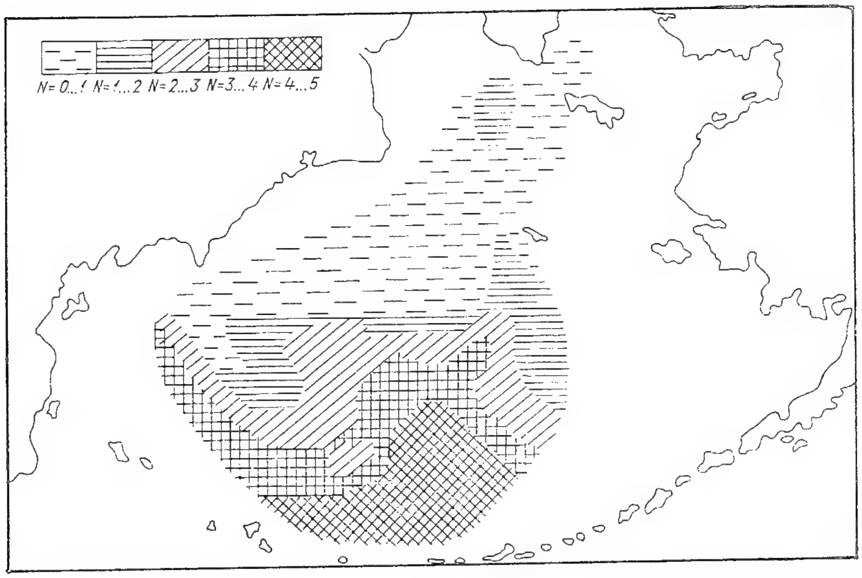

Fig. 4. Number of organisms (104 specimens/m^3) in the neustal and subneustal of the Bering Sea in July 1984.

and silicon and the numbers of small filterers–Appendicularia–may indicate that they filter out not only suspended organic matter (Alldredge 1981), but also dissolved organic compounds.

Thus, despite the severity of its natural conditions, the zooneuston of the Bering Sea is characterized by a wide variety of species and high numbers. In its characteristics, the zooneuston of 1984 differed little from the one observed in 1962 (Table 8); it had the same orders, families, and genera, and the same circadian rhythms of the temporal components of neuston. Only the massive species differed somewhat, and their numbers were appreciably higher. We attributed the difference in numbers and the absence of small forms in the 1962 sample to the fact that the collections were made with a net of larger mesh and were confined mainly to the southwestern shelf of the sea.

Such constancy of a neuston so sensitive to changes in the conditions of the medium is a rare phenomenon in our time (Zaitsev 1985). It confirms the validity of viewing the Bering Sea as a pristine region of the World Ocean (Izrael 1983). During the same length of time, the neuston of the Mediterranean, for example, underwent profound changes resulting from pollution (Krusado 1983; Zaitsev 1985). The species composition of the neuston of the two different seas—one circumpolar, the other subtropical—is obviously different. In the Mediterranean, there is a rich euneuston, which in the Bering Sea is represented by only one species of pontellids. However, meroneuston, bacterioneuston, and planktoneuston consist of representatives of the same groups of animals as in the Mediterranean. This provides the basis for drawing parallels between the fates of neuston in different ecological situations. As we have shown, in the Bering Sea, the neuston in the last two decades has not appreciably changed. For the past 20 years in the Mediterranean basin, particularly in its water areas most exposed to anthropogenic influences (i.e., in the northern Adriatic, in the bays of the Aegean Sea, the northwestern Black Sea, and other locations) the zooneuston has undergone a very serious reduction in succession, particularly noticeable among the organisms of

Table 7. *Dependence correlation between separate biotic and abiotic parameters in neustal and subneustal layers in the Bering Sea in July 1984.*

Biotic parameters	0 - 5 cm microlayer						5 - 25 cm microlayer					
	T°C	S%	NO_3	NO_2	SiO_3	PO_4	T°C	S%	NO_3	NO_2	SiO_3	PO_4
Oithona similis	+0.09	+0.59	+0.64	+0.72	+0.73	+0.62	+0.30	+0.62	+0.56	+0.71	+0.67	+0.55
Pseudocalanus minutus	+0.04	+0.18	+0.35	+0.32	+0.23	+0.36	+0.11	+0.50	+0.60	+0.65	+0.50	+0.60
Larvae	+0.23	+0.40	+0.52	+0.59	+0.28	+0.52	+0.46	+0.44	+0.44	+0.46	+0.49	+0.43
Appendicularia	-0.10	-0.34	-0.45	-0.53	-0.47	-0.50	-0.01	-0.22	-0.43	-0.45	-0.39	-0.50
Overall quality	+0.13	+0.62	+0.74	+0.81	+0.67	+0.71	+0.31	+0.64	+0.64	+0.74	+0.68	+0.62

Table 8. *Composition and average number (specimens/m³) of organisms on the surface of the Bering Sea during the summer period.*

Organisms	Microlayers, cm: June-August 1962, 0 - 5	June-August 1962, 0 - 25	July 1984, 0 - 5	July 1984, 0 - 25
Chaetognatha	7.9	9.2	64	19
Pteropoda	3.7	4.6	40	19
Cephalopoda, larvae	0.4	0.15	0	0.00
Calanus plumchrus	77.3	123.2	91	51
Calanus cristatus	13.9	19.1	–	–
Eucalanus bungii bungii	4.5	6.9	622	108
Epilabidocera amphitrites	4.8	0.12	0.7	0
Decapoda, larvae	2.8	8.2	0.2	0.13
Brachyura, larvae	5.8	1.1	0.03	0.04
Cumacea	9.1	1.2	–	–
Amphipoda	18.6	1.6	0.1	0.02
Hyperiidae	362.4	140.5	45	74
Isopoda	3.1	0.6	–	–
Euphausiacea	3.3	2.1	1	0.1
Foraminifera	–		167	94
Tintinnoinea	–	–	400	397
Oithona similis	–	–	10,709	7,111
Hydromedusae	–	–	96	35
Pseudocalanus minutus	–	–	3,526	1,453
Acartia longiremis	–	–	2,174	1,453
Appendicularia	–	–	119	87

the euneuston, for example, pontellids (Polishchuk 1977; Champalbert 1979). The numbers of meroneuston (e.g., larvae of mollusks and crabs, benthoneuston, and planktoneuston), have sharply decreased (Zaitsev 1985).

From the general trends of the progressing pollution of the World Ocean, in the Bering Sea one can also expect an intensification of this process as a result of the arrival of allochthonous substances with river, shower, and snow-melt waters, with sea currents and atmospheric precipitation, as well as a steadily increasing industrialization of the region, development of oil fields, and extraction of iron-manganese concretions. Therefore, there is no question that Tsyban et al. (1985) are correct in stating that the Bering Sea is a suitable area for a close study of the effect of increasing economic activity on a healthy marine system. A special role is assigned to neuston in these studies.

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COMPREHENSIVE EVALUATION OF THE STATUS OF THE BERING SEA PLANKTON COMMUNITY IN JUNE 1981

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During the work of a comprehensive ecological expedition on board the RV *Akademik Shirshov* in June 1981, researchers conducted a variety of studies that made it possible to evaluate the status of the plankton community of the Bering Sea. During the expedition, the basic structural characteristics of the plankton (numbers and biomass of bacterio-plankton, species composition, numbers and biomass of phytoplankton and zooplankton) and functional ones (primary and bacterial production) were determined. Their levels and distribution in the studied regions of the sea are described in detail in a monograph devoted to the results of the expedition (Lebegeva et al. 1982).

On the basis of the data obtained, the ratios and production of the heterotrophic link of plankton communities were calculated for conditions of limited food resources in accordance with a scheme developed in the plankton laboratory of the P. P. Shirshov Oceanology Institute of the Academy of Sciences of the U.S.S.R. (Izrael et al. 1987; Vinogradov and Shukshina 1987). At the present time, despite certain limitations and the preliminary nature of the calculation method employed, the scheme is uniquely suited for determining the production values of elements of multispecies plankton communities in regions of the World Ocean with a steady resupply and an extended period of reproduction of the populations (Izrael et al. 1987).

The calculations yielded data characterizing production and destruction processes in the epipelagic zone of the water areas studied, as well as the energy flux through the trophic chain of the plankton community. Their analysis makes it possible, from an ecosystem standpoint, to evaluate the status of the plankton community of the Bering Sea during the study period, get an idea of certain aspects of the sedimentation process, and select an ecological "target" of the action of "critical" concentrations of pollutants.

The present work discusses the plankton of the epipelagic region from the surface down to 100 m. The preparation for the calculation of data on the structure of the plankton community consisted, first, in separating out the elements of the community with allowance for the taxonomic, dimensional, and trophic characteristics of the aquatic organisms. Their composition, caloric content, and the values of the coefficients used in the calculation (Dagg et al. 1982; Izrael 1987; and Ikeda and Motoda 1978) are reflected in Table 1. On the basis of literature data on the trophic structure of the plankton communities of the epipelagic region of subarctic and highly productive regions of the World Ocean

Table 1. *Characteristics and composition of elements of the plankton community.*

Group	Element	Symbol	K_2^{max}	Assimilability	Caloric content, cal/mg gr weight	Composition of elements
Phytoplankton	Small (<15 μm)	p_1			1.0	
	Large (>15 μm)	p_2			0.6	
Bacterioplankton	Bacterioplankton	b	0.5	1.0	1.0	
Protozoans	Zooflagellates	a_1	0.6	0.7	1.0	
	Infusorians	a_2	0.6	0.7	0.8	
Mesozooplankton (0.1-3.0 mm)	Fine nannophage filterers	f	0.6	0.7	0.7	Copepod nauplii, copepodite stages of fine calanid genera *Microcalanus, Pseudocalanus, Acartia*, larvae of mollusks, polychaetes, echinoderms; rotifers, appendicularians
	Euryphages	v	0.5	0.7	0.7	Younger copepodite stages of calanid genera *Calanus, Eucalanus*, older copepodites of calanid genera *Acartia, Pseudocalanus,* cyclopods, harpacticoids, ostracods
					0.35	Nonpredatory pteropod mollusks
	Predators	s	0.5	0.7	0.7	Decapod larvae, sideswimmers, nemertineans, polychaetes
					0.35	Predatory pteropods
					0.4	Arrowworms
					0.05	Siphonophores, medusae, ctenophores

Table 1. *Continued.*

Group	Element	Symbol	K_2^{max}	Assimilability	Caloric content, cal/mg gr weight	Composition of elements
Mesozooplankton (3.0 - 30 mm)	Euryphages	g	0.5	0.7	1.0	Older copepodite stages of calanid genera *Calanus*, *Eucalanus*, euphausids

(Cooney and Coyle 1982; Lebegeva 1982; Shukshina 1984; Vinogradov and Shukshina 1987), a diagram of the trophic relations between the elements was drawn, and values of feeding selectivity coefficients, I, were estimated (Table 2). I takes the values 1.0, 0.5, 0.2, and 0. In this case, when all the organisms making up the consumer element are able to consume all the organisms making up the prey element, I is given the maximum value of 1.0. Depending on the ability of one element to consume the other, I assumes the value 0.5 or 0.2. If there is no trophic relation between the elements, I = 0.

To determine the metabolic rate of heterotrophic organisms (infusorians and mesozooplankton), use was made of the general dependence R(w) for marine zooplankton at a water temperature of 20°C, obtained at the P. P. Shirshov Oceanology Institute of the Academy of Sciences of the U.S.S.R. (Vinogradov and Shukshina 1987);

$$R = 0.6w^{0.8}$$

where R is measured in mcal organisms^{-1} day^{-1}, and w in mcal organisms^{-1}.

A correction for temperature allowing for Q_{10} = 2.2 was introduced into the values of the zooplankton metabolic rate. The equation used in the calculation is in good agreement with that given by U.S. scientists for the herbivorous zooplankton of the southeastern Bering Sea (Dagg et al. 1982) for an average caloric content of zooplankton of 0.7 cal/mg gram weight.

The value of R/w for zooflagellates, equal to 250%, remained constant in all the calculations, and the respiration expenditure of the bacterioplankton was calculated from the production measured in situ using C^{14} and from the value K_{2B} = 0.33 (Vinogradov and Shukshina 1987).

The studies were conducted at four polygons located in the western, northern, eastern, and southern Bering Sea (frontispiece). The heterogeneity of the conditions of functioning of the plankton communities in the areas of the polygons accounted for the difference in the stages of seasonal plankton development during the studies. As a community matures, a change takes place in the rates of the processes of production and heterotrophic destruction of organic matter. Their relative levels make it possible to assess the stage of development of the pelagial community to which corresponds a specified trophic character level of the water populated by them. To describe the patterns of development of the communities, all the stations at the polygons were grouped according to the trophic characteristic levels. As the criterion for determining trophic character, use was made of the following ranges of the ratios of the primary production level to the overall heterotrophic

Table 2. *Chart of trophic relations and nutrition selectivity coefficients (I).*

Consumer element[a]	Prey element							
	b	a_1	a_2	f	v	p_1	p_2	d[b]
b	0	0	0	0	0	0	0	1.0
a_1	1.0	0	0	0	0	0	0	1.0
a_2	1.0	1.0	0.2	0	0	1.0	0.2	0.5
f	0.5	1.0	0.5	0	0	1.0	0.5	0.2
v	0.2	0.5	0.5	0.2	0.2	0.5	1.0	0.2
g	0	0	0.2	0.5	0.2	0.5	1.0	0.2
s	0	0	0.2	0.5	0.5	0	0	0

[a]See Table 1 for symbol definitions
[b]d — dead organic matter

destruction level: $K_m > 2$ — heterotrophic, $2 > K_m > 0.7$ — eutrophic, $0.7 > K_m > 0.3$ — mesotrophic, and $0.3 > k_m$ — oligotrophic waters (Petina 1981).

Structural Characteristics of Plankton Communities

A change in the level of the trophic character of the waters at the stations was accompanied by a change in the structural characteristics of the communities inhabiting the epipelagic region; this was manifested with particular clarity in the regions of the western and northern polygons (Table 3).

At the west polygon, the total biomass of the plankton community amounted to an average of 53.0 kcal/m^2. At a majority of the stations (nos. 2, 3, 4, 6) in highly productive waters, the fraction of phytoplankton was 32%; bacterioplankton, 9%; and zooplankton, 59% of total biomass. A major portion of the latter group consisted of large euryphages: about 59% of mesozooplankton biomass. The breakdown of the structure of the community at stations 5 and 8 and a general decrease of phytoplankton biomass led to a marked reduction of the trophic character of the waters down to the oligotrophic level. The breakdown was caused by the development, abnormally high in this region, of the microzooplankton component of the heterotrophic link in one case, and of the bacterioplankton component in the other case. Altogether during the studies, reproduction and massive development of nauplial and younger copepodite stages of interzonal species of copepods took place, causing high values of the small-sized fraction of mesoplankton.

In the area where the depth increased rapidly, maximum values of the total biomass of the communities were recorded during the period studied: they exceeded an average of 80 kcal/m^2 in mesotrophic waters. In comparison to the highly productive waters of the western region, at the east polygon a reduction of the content of primary producers and nannophages in the plankton took place. There was a corresponding increase in the fraction of microzooplankton and small-sized euryphages and large euryphages (down to 72% of the mesozooplankton mass). Despite the difference in the trophic character levels of the waters at the deepwater and shallow-water stations of the east polygon, no significant structural rearrangements associated with this difference were found in the pelagic community.

Table 3. *Structural characteristics of the plankton community.*

Polygon	Station no.	Trophic character of waters	P_p/D_o	B_o Kcal/m²	B_i/B_o% p	b	z	B_i/B_z, % a_1	a_2	B_i/B_m, % f	v	g	s
West	2,3,4,6	Hyper-eutrophic	1.91	56.0	32	9	59	0.2	6.0	15	16	59	8
	5,8	Oligo-trophic	0.16	50.0	14	11	75	0.2	11.4	20	16	57	8
	19,23,24, 25,26,27	Eutrophic	1.42	65.3	20	12	68	1.9	12.5	7	24	67	2
East	20,21,22	Meso-trophic	0.53	81.1	15	6	80	1.2	8.2	4	22	72	1
South	31,32	Eutrophic	1.67	56.9	18	11	71	1.6	8.3	13	17	69	2
	28,29,30 33,34,35	Meso-trophic	0.43	65.0	7	26	68	1.2	5.2	12	23	62	3
	10,11,12	Hyper-trophic	12.49	40.8	65	11	24	3.0	22.3	38	36	23	3
	13,14 15,16	Eutrophic mesotrophic	0.97	50.1	72	8	18	3.2	33.7	48	30	19	4
	17,18	Oliogo-trophic	0.14	24.2	51	17	32	4.3	23.7	53	40	2	5

Symbols: B_o — biomass of the plankton community; P_p — production of phytoplankton; D_o — heterotrophic destruction of the community; B_i — biomass of the elements of the community: z — zooplankton, m — mesozooplankton.

A majority of the stations in the southern region of the Bering Sea (the south polygon) were characterized by a mesotrophic level of the waters. In a number of the inspected areas of the central deepwater region of the sea, a further reduction in phytoplankton content to 7% of the total biomass of the community took place in the plankton community of the south polygon. The bacterioplankton biomass increased significantly. The massive development of the *Oithona similis* population caused high biomass values of nannophages (nauplii of small crustaceans).

In the deepwater regions of the Bering Sea, as the trophic character level of the waters decreased, the structure of the plankton communities changed. In order of examination of the regions studied, from the west polygon to the east polygon, a gradual decrease of the phytoplankton biomass took place, along with an increase in the content of representatives of heterotrophic elements in the plankton.

In the shallow shelf region of the Bering Sea (the north polygon), the plankton community was in different stages of succession. The total

plankton biomass had its maximum value in eutrophic-mesotrophic waters and reached 50 kcal/m^2 in the 0- to 45-m layer. In waters of lesser trophic character, the value of this index dropped sharply, by more than one-half. In hypertrophic waters, intermediate levels of this index were recorded: 41 kcal/m^2. The phytoplankton biomass changed in the same order. In eutrophic-mesotrophic waters, algae comprised over 70% of the plankton biomass. Both the absolute and relative levels of the phytoplankton content in waters of the northern region of the studies were maximum for all the investigated water areas of the Bering Sea. Changes in reverse order were noted in heterotrophic groups of aquatic organisms, and the values of the basic structural characteristics exhibited a medium level in the most productive hypertrophic waters. The bacterioplankton and zooplankton played a minimal role in the community inhabiting eutrophic waters. The low biomass of large euryphages was conducive to an increase in importance of microzooplankton elements, as well as nannophages and small euryphages in waters of the shelf region of the Bering Sea.

Productive-Destructive and Trophic Characteristics of Communities

The rate of generation of organic matter in deepwater regions of the Bering Sea (west, east, and south polygons) had similar values in waters of equal trophic character (Table 4). In hypertrophic and eutrophic waters, the level of primary production ranged, on average, from 6.8 to 7.3 kcal m^{-2} day^{-1}. In waters of lesser trophic character, the value of this index decreased by a factor of 2:7.

The levels of production of heterotrophic elements reflected the basic structural characteristics of the plankton communities and the trophic conditions of their existence. The high biomass levels of the food items in all the studied areas of the Bering Sea determined a high degree of satisfaction of the food requirements of plankton animals and created the conditions for the formation of maximum possible levels of zooplankton production. The growth rates of the microplankton and mesozooplankton groups of aquatic organisms were similar and varied from 0.8 to 2.4 kcal m^{-2} day^{-1}. Their maximum levels were confined to low-production water areas: microzooplankton up to 2.2 kcal m^{-2} day^{-1} at the west polygon, and mesozooplankton up to 2.4 kcal m^{-2} day^{-1} at the south polygon.

Analysis of the production-rate values showed that the P/B, the phytoplankton coefficient in highly productive regions of the sea, was 2-4 times that of the mesotrophic and oligotrophic waters. At the same time, local "blooms" were noted at individual stations of the east and south polygons. In these regions, low biomass levels were associated with high levels of specific production of phytoplankton. The specific production of bacterioplankton approximately doubled as the productivity of the communities in the western and eastern regions of the Bering Sea decreased. At the south polygon, a sharp increase in biomass of the microflora resulted in an appreciable decrease of the values of the P/B coefficient, down to 0.3/day.

The specific production of the functional groups of zooplankton reacted much less to a change in water supply of the waters as compared to phytoplankton and bacterioplankton. The rate of production of microzooplankton varied in the range 0.29-0.54/day, and that of mesozooplankton organisms, in the range 0.04-0.06/day.

The overall magnitude of heterotrophic destruction characterizes the amount of energy scattered in the plankton community and formed by autotrophic organisms in the epipelagic region. Its values are more constant than other structural and functional characteristics. However, a tendency toward an increase in the level of overall destruction of heterotrophs in the water areas of the deep regions of the Bering Sea of low trophic character was also

Table 4. *Production-destruction characteristics of plankton communities.*

Polygon	Trophic character of water	P_i = kcal m^{-2} day^{-1}				P_i/B_i day^{-1}				P_o kcal m^{-2} day^{-1}	D_o kcal m^{-2} day^{-1}	R_i/D_o, %		
		p	b	a	m	p	b	a	m			b	a	m
West	Hyper-eutrophic	6.9	0.6	0.8	2.0	0.42	0.15	0.48	0.06	3.20	3.68	36	16	48
	Oligotrophic	1.0	1.1	2.2	1.8	0.20	0.26	0.46	0.06	-6.27	7.27	32	34	34
East	Eutrophic	6.3	0.5	2.0	1.4	1.06	0.08	0.33	0.05	1.70	6.12	24	32	44
	Mesotrophic	3.4	0.9	1.7	1.8	0.28	0.19	0.29	0.04	-3.16	7.46	29	30	41
South	Eutrophic	7.3	0.5	1.4	1.8	2.69	0.08	0.41	0.06	2.93	4.38	22	29	49
	Mesotrophic	1.9	0.5	1.2	2.4	0.59	0.03	0.54	0.06	-2.72	4.65	20	21	59
North	Hypertrophic	23.3	0.4	0.9	0.5	0.85	0.10	0.36	0.06	21.45	1.88	46	30	23
	Eutrophic-mesotrophic	1.9	0.4	1.0	0.4	0.05	0.12	0.30	0.07	-0.54	2.03	43	36	21
	Oligotrophic	0.2	0.3	0.6	0.4	0.02	0.07	0.30	0.05	-1.34	1.51	40	29	31

Designation: P_i = Production of elements of the community, $P_o = P_p - D_o$ - net production of the community.

R_i = Waste on respiration of elements of the community, other symbols are the same as in Tables 1 and 3.

noted in this case. These changes, like the decrease in the levels of primary production in mesotrophic and oligotrophic waters, caused a substantial deficiency of newly formed organic matter and a change in the values of net production of the plankton community (P_0) to negative values. At deepwater polygons, mesozooplankton played a dominant role in the total energy of destructive processes, and its respiration expenditure in the southern polygon in mesotrophic waters amounted to an average of 59% of the total destruction of heterotrophs. The contribution of bacterioplankton in the western polygon did not exceed 36%, and in the southern polygon, 22%.

The conditions of functioning of the plankton organisms and the intensity of the trophic relations of the aquatic organisms determined the magnitude of their real specific production (ξ), which showed how the biomass of an element changed as a result of its representatives being consumed (Table 5).

In the mesotrophic and oligotrophic waters of the areas studied, the phytocene underwent heavy consumption, and the production of algae was insufficient to maintain the existing biomass levels in the majority of cases. A similar situation was observed in the relationships between consumers and bacterioplankton, whose biomass decreased not only in mesotrophic waters but also in hypertrophic and eutrophic ones. Under these conditions, a process of increase of the biomass of mesoplankton groups, especially microzooplankton, was observed. Only in the southern polygon did the high intensity of the trophic chain and low concentration of "primary food" lead to a decrease in the biomass of nannophages and small euryphages.

There was a distinct decreasing trend of the ξ values of dead organic matter, including detritus and dissolved organic matter, from the western study area, most productive in the oceanic region, to the mesotrophic waters of the southern polygon. This indicated a rearrangement of the trophic relations and changeover of the plankton community to the detritus food chain in the southern polygon. The ratio of the magnitude of energy (P) assimilated by bacteria and other detritophages to the magnitude of the energy of dead organic matter and phytoplankton assimilated by all the heterotrophs of the family assumed the maximum value of over 80% in the southern polygon. In other areas, a major portion of the energy used by heterotrophic plankton organisms was supplied directly by the consumption of autotrophs.

To cover the energy expended in vital activity and growth, the animals used various food items, substituting for others some that were more abundant and accessible to consumption in the case of a deficiency. At the west polygon, a major portion of the zooplankton ration was provided by the high phytoplankton biomass. The ratio of the levels of consumption of algae and of the zooplankton ratio (E_p/C_z) reached 70% in this area. At the east and south polygons, the fraction of phytoplankton in the ration of the animals was much smaller, and at the southern polygon it even lost its dominant role. Under these conditions, there was a compensatory increase in the consumption of bacterioplankton (40%), small mesoplankton organisms (19%), and dead organic matter (13%).

In its geographical position and specific ecological conditions of the plankton community, the north polygon occupied a special position among the investigated areas of the Bering Sea. Shallow waters, low temperature of the water masses, and the presence of upwelling in the north of the polygons gave special features to the character of the functioning of the pelagic community.

In the upwelling area (stations 10-12), record high primary production values, on the average, 23.3 kcal m^{-2} day^{-1}, were recorded for the study period (Table 4). As one moved southward within the water area of the polygon, the autotrophic production of organic matter decreased,

Table 5. *Trophic-ecological characteristics of plankton communities.*

Polygon	Trophic character of water	$(\xi) = C_i/C_i^{max}$		$(\xi) = P_i - E_i/B_i$				E_i/C_z, %					(ρ) %
		a	m	p	b	a	m	p	b	a	m	d	
West	Hypertrophic-eutrophic	0.95	0.97	0.13	-0.05	0.31	0.03	68	12	4	13	3	36
	Oligotrophic	0.76	0.83	-0.54	-0.43	0.01	0.01	42	27	12	15	4	52
East	Eutrophic	0.85	0.93	0.72	-0.44	0.16	0.02	44	28	13	6	9	49
	Mesotrophic	0.84	0.93	-0.12	-0.29	0.22	0.01	43	23	17	9	8	47
South	Eutrophic	0.84	0.87	2.08	-0.38	0.06	0.03	34	29	12	15	10	54
	Mesotrophic	0.89	0.89	0.04	-0.25	0.21	0.02	21	40	7	19	13	81
North	Hypertrophic	0.98	0.99	0.74	-0.08	0.28	0.06	71	21	4	2	2	43
	Eutrophic-mesotrophic	0.98	0.99	-0.05	-0.08	0.25	0.06	76	17	4	1	2	37
	Oligotrophic	0.96	0.98	-0.14	-0.17	0.20	0.06	55	31	7	3	4	45

Designations: E_i - Corrosion of the biomass of element, C_i - ration of element, C_i^{max} - maximal ration of element. Other designations are the same as in Tables 1, 3, 4 and for the text.

and reached the minimum level of 0.2 kcal m^{-2} day^{-1} in oligotrophic waters. Among the heterotrophic elements of the community, the rate of growth of microzooplankton appreciably surpassed the analogous characteristics of bacterioplankton and mesozooplankton, particularly in eutrophic-mesotrophic waters: 1.0 and 0.4 kcal m^{-2} day^{-1}, respectively.

The relatively low production rate and high biomass of phytoplankton beginning to die off caused a very insignificant rate of the production process in eutrophic, mesotrophic and oligotrophic waters, comparable to the specific productivity of mesozooplankton elements (0.02-0.05/day). In comparison to the oceanic regions of the Bering Sea, the total heterotrophic destruction decreased by a factor of 2-3 at the north polygon, and its level was about 2 kcal m^{-2} day^{-1}. In this connection, the magnitude of the net production of the community P_o was almost identical to the magnitude of the production of autotrophs. At the same time, in eutrophic, mesotrophic and oligotrophic waters, P_o took negative values: -0.54 to -1.34 kcal/m^2 day. A fundamental role in the destruction processes was played by bacterioplankton (40%-46%) and microzooplankton (29%-36%). The fraction of mesozooplankton accounted for no more than 31%.

The actual specific production (ξ) of the main elements of the community had values close to those observed in the deepwater areas of the Bering Sea, and analogous changes in waters differing in trophic character (Table 5). We shall only note an increase in values for bacteria and mesoplankton, as well as an intensive accumulation of dead organic matter in the epipelagic region, caused by a massive "bloom."

The nutritional requirements of zooplankton in hypertrophic and eutrophic waters were met by phytoplankton to the extent of over 70%. Combined with bacterioplankton, their fraction in the ration exceeded animals by 90%. In oligotrophic waters, the value of algae as a food item for zooplankton dropped to 55%.

Conclusion

In the surface waters of the west, east, and south polygons more than half of the total biomass of the community (60%-70%) was represented by heterotrophic organisms, and to a significant degree by mesozooplankton organisms. The respiration expenditure by this biomass made the main contribution to the total heterotrophic destruction of the community.

The western polygon was characterized by a eutrophic level of the surface waters. A relatively high phytoplankton biomass caused a high degree of satisfaction of the food requirements of zooplankton. Seventy percent of food intake consisted of algae. In the epipelagic region, in the course of 24 h, the functioning of the plankton community resulted in the accumulation of biomass of phytoplankton, microplankton, and mesozooplankton, as well as dead organic matter.

At the east polygon, the level of trophic character changed from eutrophic in the deepwater portion of the polygon to mesotrophic at the shelf boundary. Compared to the west polygon, the phytoplankton content of both the total biomass of the community and of the ration of plankton animals decreased appreciably, the role of microheterotrophs and dead organic matter in the nutrition of the consumers increased, and the level of the net production of the community dropped.

The predominance of the mesotrophic level of the waters at the south polygon resulted in an even greater reduction of the role of autotrophs in the structure and functioning of the plankton community. An acute deficiency of newly formed organic matter caused a changeover of the pelagic community to the detrital type of food chain. The level of dead organic matter assimilated by the aquatic organisms exceeded the level of autotroph energy assimilated by the community. The rate of the processes of destruction of organic matter predominated over

the rate of the processes of its production; the net production of the community had negative values.

At the north polygon, the structure of the plankton community differed appreciably from that observed at the deepwater polygons. Autotrophic aquatic organisms predominated in biomass in the plankton. The zooplankton was in the initial stage of seasonal development, and its biomass was low. In the area of the upwelling, maximum levels of primary production were recorded during the period studied. In the eutrophic and mesotrophic waters surrounding the production epicenter, accumulation of organic matter took place, and at the periphery of the polygon in oligotrophic waters, the phytoplankton biomass dropped sharply owing to the sedimentation of dead algae and their consumption by phytophages. Favorable trophic conditions for the functioning of heterotrophs at the polygon determined high levels of their actual specific production. The overall heterotrophic destruction was formed to a large extent as a result of the metabolism of bacterioplankton and microzooplankton. The net production of the plankton community in hypertrophic waters was maximum and comparable to the levels of the primary production rate. In waters of lesser trophic character, the net production dropped to negative values.

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Benthos

BENTHOS OF THE BERING SEA

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At the present time, increasing emphasis is being placed on the study of the impact of anthropogenic influences on the marine biota. Information on the ecological aftereffects of pollution of the ocean is particularly important. In areas exposed to significant anthropogenic influences, stable changes in the structure and functioning of marine communities are observed. They are manifested in a change in average biomass of populations of planktonic and benthic organisms, a decrease in the number of higher taxa of aquatic organisms, the appearance of organisms new to the marine environment, and a change in the relationships between the numbers of individual taxonomic groups of aquatic organisms (Izrael et al. 1982).

To study the structure and functioning of marine ecosystems and predict their changes resulting from anthropogenic influences, researchers are conducting studies involving ecological monitoring in the impact and background regions of the ocean (Tsyban et al. 1985). Background regions include the Bering Sea, one of the productive seas bordering the U.S.S.R. which is not exposed to significant anthropogenic influences (Izrael et al. 1982). One of the indicators of complex ecological monitoring of the Bering Sea is benthos (Izrael et al. 1982), and particularly meiobenthos, a necessary component of bottom-dwelling communities that is more sensitive to environmental changes than macrobenthos.

Detailed studies of the quantitative distribution of benthic organisms of the Bering Sea were conducted in the 1930's, 1950's, and 1960's (Vorob'ev 1945; Neiman 1963; Lus 1970). An expedition of TINRO (Pacific Ocean Scientific Research Institute of Fisheries and Oceanography) and VNIRO (All-Union Scientific Research Institute of Sea Fisheries and Oceanography) was conducted in 1957-60 for determining the fish stocks of the Bering Sea and studying the environmental factors affecting the distribution and size of the stocks. Considerable attention during this expedition was focused on benthos. Over an extensive area of the shelf, from the Gulf of Anadyr to southeast of Bristol Bay, benthos was collected from a wide network of stations (Neiman 1963; Filatova and Barsanova 1964; Althon 1972). As a result of these studies, the qualitative and quantitative composition of the macrozoobenthos of the Bering Sea was determined with its zoogeographical classification, the biomass of the food benthos of different areas of the sea was established, and the biocoenoses of the northwestern and eastern portions of the Bering Sea were identified. After a 20-year interruption, a study of Bering Sea benthos was begun under a program of background ecological monitoring. The first data on the composition and structure of macrobenthos communities of the Bering Sea under this program were obtained during the 27th cruise of the RV *Akademik Shirshov* in 1981. The studies were continued in June-August 1984 during the 37th cruise of the RV *Akademik Korolev*.

The aim of the benthos work during the 37th cruise of the RV *Akademik Korolev* was the study of the distribution of the bottom fauna and structure of the benthos communities in the Bering Sea. The following objectives were set: to collect data and form a general idea of

the benthos of the investigated regions of the Bering Sea; to study its quantitative distribution and qualitative composition, and the influence of environmental factors on its distribution; and to compare the data obtained during the 37th cruise of the RV *Akademik Korolev* with the data of the 27th cruise of the RV *Akademik Shirshov* and with data on Bering Sea benthos reported in the literature.

A study of meiobenthos communities was also carried out. Meiobenthos, an evolutionarily formed subdivision of benthos that combines animals of specific systematic groups, is an intermediate link between microorganisms and macroorganisms (Neiman 1963). Because a majority of the contaminants distributed in the water mass of the ocean are sorbed on suspended matter and accumulate in bottom sediments (Izrael et al. 1982), and meiobenthos organisms react more quickly to a change in abiotic environmental factors, this was the category of animals that was studied.

Material and Study Areas

The benthos studies were conducted at four polygons with one side approximately equal to 1°, and collections were made on sections between the polygons (Table 1; frontispiece).

The benthic distribution is considerably affected by the water masses in contact with the bottom. In the Bering Sea, four water masses encompassing different depth intervals were distinguished as follows: 0-50 m (surface mass), 50-200 m (intermediate cold mass), 200-700 m (intermediate warm mass), and greater than 700 m (deep mass) (Gol'tsova 1971). The observation polygons were located in water masses of different qualities.

Stations of the south polygon were located in the deep-sea portion of the Aleutian Basin south of the Bowers Ridge in the zone of the Aleutian upwelling. The dominant sediment was pelitic-diatomaceous ooze. At this polygon, two bottom samples and one trawl sample were taken.

The east polygon was located on a steep continental slope in the area of Zhemchuzhnyy Canyon, which ranged from 133 to 3,171 m in depth. At this station, a varied sediment, oozy and sandy, was noted. From this polygon, six bottom samples and three trawl samples were obtained.

The stations of the north polygon were located on the Continental Shelf of St. Lawrence Island in a cold intermediate mass zone with a depth range of 50-70 m. In the composition of the sediments, clay ooze predominated, often with a smell of hydrogen sulfide; coarse sand, gravel, and pebbles were also present, and fairly large stones and boulders were encountered. Fourteen bottom samples and one trawl sample were taken from the polygon. At two stations of the section, between the second and third polygon, four bottom samples and one trawl sample; at station 18, between the north and west polygons, two bottom samples were taken.

The west polygon was located on the slope of the Shirshov Ridge. At depths of 630 to 1,320 m, four bottom samples and one trawl sample were taken.

At the polygons and sections studied, 31 representative bottom samples and six trawl samples were obtained.

In collecting the benthos samples, two standard pieces of equipment were used: an Okean-50 bottom sampler, with a grabbing area of 0.25 m^2, and a Sigsby trawl with a grabbing width of 1.5 m. The bottom samples obtained were washed through sieves with a cell diameter of 5 mm by 1 mm. The collected fauna was preserved with 4% formaldehyde and 75° alcohol.

Meiobenthos was collected at three stations in the western area (20, 21, 24), which were confined to depths of 630-1,302 m, one station in the southern area (25) at a depth of 4,000 m, six stations in the north (12, 13, 14, 15, 17, 18), and four stations in the east (6, 8, 10, 11).

Table 1. *Benthic stations studied during 37 voyages on the scientific RV* Akademik Korolev.

Station no.	Data	Depth (m)	Sampling Coordinates	
3	03.07.84	3,946	53°11'5" N	175°20'9" E
4	06.07.84	3,770	52°45'8" N	178°22'3" E
6	08.07.84	2,717	57°59'85" N	175°05'76" W
8	09.07.84	146	57°30'0" N	173°53'8" W
9	10.07.84	133	58°32'0" N	174°09'2" W
10	11.07.84	97	59°07'84" N	174°01'5" W
11	12.07.84	72	61°28'9" N	173°39'7" W
12	12.07.84	69	63°04'8" N	173°29'3" W
13	13.07.84	55	63°59'4" N	173°27'5" W
14	13.07.84	50	64°21'0" N	171°23'0" W
15	14.07.84	50	62°57'4" N	172°26'7" W
16	14.07.84	55	63°58'7" N	172°17'6" W
17	15.07.84	61	63°24'4" N	172°42'8" W
18	16.07.84	72	62°44'1" N	174°37'1" W
20	20.07.84	630	58°35'56" N	170°28'10" W
21	21.07.84	1,302	58°06'0" N	170°08'1" W
24	23.07.84	995	57°27'7" N	170°43'7" W
25	25.07.84	3,935	53°44'6" N	176°21'7" W

To study the meiobenthos with a weighing bottle having an area of 18.1 cm^2, three subsamples were taken from different portions of the surface of a soil core sample raised by the bottom sampler. The weighing bottle collected a 4-cm layer of bottom sediments. In the laboratory, the sediment was washed through sieves, the lowest of which had a diameter of 0.13 mm. Collected organisms were stained with Bengal rose. All the organisms in the sample were counted and removed. Data on individual weights of the meiobenthic organisms were used to calculate the biomass (Vorob'ev 1949; Gol'tsova 1971). The average individual weight of Bering Sea nematodes after determination of the average size characteristic was calculated from the nomograms of Chislenko (1968). The present report cites information on meiobenthos at the level of higher taxa. Three groups of meiobenthos were not identified; therefore, at this stage they were classified as "other," and their biomass was not considered.

Characteristics of Macrobenthos

Analysis of the collected material confirms the existing view of the abundance of the bottom fauna of the Bering Sea and diversity of its quantitative and qualitative distribution. Data on the numbers and biomass of the zoobenthos organisms are listed in Tables 2 and 3.

At the deep-sea stations of the south, east, and west polygons, an extremely poor fauna was noted, this being characteristic of large depths, and the benthos biomass of these areas was also low. The lowest biomass (4 g/m^2) was noted at station 6, located at the base of the continental slope. In the bottom sample at this station, polychaetes dominated in biomass, and mollusks of the genus *Thyasira* were encountered. The trawl lowered at this station covered a wide range of depths (2,737-3,046 m). The catch included much gravel and many boulders and rocks of volcanic origin resembling

Table 2. *Density (numerator, specimen/m^2) and biomass (denominator, g/m^2) of various taxa of macrobenthos at stations in the Bering Sea.*

Taxa	Station No. 3	6	8	9	10	11	12	13	14	15	16	17	18	20	21	24
Foraminifera	-/36.00	-	-/0.10	-/1.60	18/0.60	-	-	-	-	-	-/0.10	-	-	-/0.10	-	-/0.10
Spongia	-	-	-	-	-	-	-	-/6.80	-/462.0	-	-	-	-	-/244.0	-	-/120.00
Hydrozoa	-	-	-/0.10	-	-/0.10	-	-	-/12.0	-	-	-/0.20	-	-	-	-	-
Anthozoa	-	-	-	-	4/0.10	-	-	56/25.0	-/1.30	-	-/9.00	-	-	-	-	-
Actiniaria	-	-	-	-	-	-	-	-	-	-	26/4.00	6/-	-	4/1.00	12/-	-
Nemertini	-	-	-	-	2/0.10	-	8/2.20	6/14.0	-	-	16/6.40	16/6.40	6/19.2	-	4/0.60	-
Priapulida	4/0.10	-	-	-	4/0.60	16/0.50	-	-	-	-	-	-	8/1.20	-	-	
Polychaeta	-	72/3.20	300/12.0	200/2.50	226/56.00	376/27.0	308/17.4	188/17.4	163/19.0	436/66.0	286/12.0	342/460	180/40.0	240/24.0	84/38.40	28/11.00
Echiurida	-	-	-	-	-	64/120	-	-	-	-	-	-	-	-	-	-
Sipuncula	4/0.10	-	-	-	-	-	-	-	-	-	-/0.70	-	2/36.0	-	-	
Bryozoa		-	-	-	-	-	-	-	-/1.80	-/1.00	-	-/2.00	-	-	-	-
Cumacea	-	-	-	-	24/0.10	4/0.10	4/0.10	2/0.10	2/0.10	14/0.20	8/0.10	-	8/0.10	22/0.10	72/0.80	40/0.60

Table 2. *Continued.*

Taxa	Station No. 3	6	8	9	10	11	12	13	14	15	16	17	18	20	21	24
Amphipoda	-	-	6/0.10	40/0.50	14/0.60	192/1.60	132/0.90	22/0.10	10/0.10	586/14.3	8/155	1936/0.10	96/7.60	74/1.80	28/0.80	-/-
Decapoda	-	-	-	2/0.10	-	12/28.0	-	-	-	2/0.80	-	-	2/3.60	-	-	-
Loricata		-	-	-	-	-	-	-	-	8/0.50	26/2.70	-	16/1.20	-	-	-
Gastropoda	-	-	-	16/0.80	8/0.80	4/0.80	-	16/2.00	4/1.40	4/6.00	52/2.20	2/1.80	52/3.40	16/3.40	-	12/2.00
Bivalvia	4/0.10	8/0.60	54/-	32/5.00	112/22.0	608/138	316/166	22/16.0	22/20.5	366/278	70/50.0	144/38.0	134/106	-	60/3.60	4/0.10
Ophiuroidea	-	-	470/11.4	338/0.70	486/13.6	696/45.0	8/22.0	2962/61.0	-/30.0	90/65.0	514/7.70	12/4.80	62/32.0	32/3.20	32/17.2	8/0.20
Echinoidea	-	-	-	-	-	-	-	52/138	84/572	-	40/102	-	-	-	-	-
Ascidiae	-	-	-	-	2/-	-	-	2/3.00	-	-	-	8/37.0	-	-	412/0.10	-
Holo-thurioidea	-	-	-	-	-				6/1.00	-	-	-	-	-	12/4.10	-
Enter-opneusta	-	-	-	-	-	-				2/0.60	-	-	-	-	-	-
TOTAL	12/40.0	280/3.80	830/25.0	624/11.0	874/96.0	2032/304	787/217	3498/295	1820/113	1288/431	1254/191	2404/249	714/248	330/278	452/67.0	300/142

Table 3. *Density of colonies (numerator in thousands of specimens/m^2) and biomass (denominator, mg/m^2) of various taxa of meiobenthos at stations in the Bering Sea.*

Taxa	Station No.													
	6	8	10	11	12	13	14	15	17	18	20	21	24	25
Foraminifera	29.7/386.1	18.9/245.7	7.5/97.5	12.7/165.3	215.5/2801.8	15.2/197.5	32.0/416.0	83.2/1089.4	328.4/4269.2	19.2/249.6	12.6/163.8	53.4/694.2	17.3/225.0	0.6/7.2
Nematoda	223.8/138.8	267.6/166.0	732.2/454.0	917.1/568.6	1150.3/713.2	484.9/300.7	654.3/405.7	1290.7/800.2	1732.3/1074.0	2344.4/1455.6	26.5/16.4	256.2/168.9	281.5/174.5	20.8/12.9
Harpacticoida	1.9/14.7	4.4/35.2	0.6/4.4	13.3/106.4	-	1.7/13.6	27.9/223.3	6.1/48.8	9.0/72.0	3.1/25.0	0.3/2.4	0.8/6.4	1.7/13.6	0.9/7.4
Kinorhyncha	-	-	-	5.0/25.0	-	-	0.6/3.0	-	1.1/5.5	3.3/16.5	-	-	-	-
Ostracoda	-	-	-	0.3/1.8	-	0.6/3.9	3.9/25.4	-	3.7/24.0	-	-	-	-	0.4/2.4
Halacarida	0.2/12.5	-	-	0.3/20.4	0.6/40.8	-	-	-	-	-	0.3/20.4	0.3/20.4	0.2/12.5	0.2/12.5
Eumeio-benthos	255.6/552.1	290.9/446.9	740.3/555.9	948.7/887.5	1366.4/3555.8	502.4/515.7	718.7/1073.4	1380.6/1958.4	2074.5/5444.7	2370.0/1744.7	39.7/203.0	310.7/889.9	300.7/425.6	22.9/42.4
Polychaeta	2.4/122.1	1.4/71.4	1.9/96.9	2.2/112.2	-	1.4/69.1	9.7/494.7	1.4/71.4	3.3/168.3	-	-	2.8/142.8	1.9/96.9	1.1/55.3
Oligochaeta	0.2/2.2	1.6/17.6	4.4/48.7	-	-	1.9/21.0	10.5/115.5	-	1.1/12.1	4.4/48.7	-	-	-	-
Mollusca	-	0.7/280.0	0.3/120.0	2.5/994.8	0.3/120.0	0.6/240.0	0.8/320.0	2.2/880.0	41.3/16520.0	1.7/680.0	-	0.3/120.0	-	0.2/73.8

Table 3. *Continued.*

Taxa	Station No. 6	8	10	11	12	13	14	15	17	18	20	21	24	25
Sipuncula	-	-	0.3 / 13.9	-	-	-	-	0.3 / 13.9	-	-	-	-	-	-
Psedomeio-benthos	2.6 / 124.3	3.7 / 369.0	6.9 / 279.5	4.7 / 1107.0	0.3 / 120.0	3.9 / 330.1	21.0 / 930.2	3.9 / 965.3	45.7 / 16700.4	6.1 / 728.7	-	3.1 / 262.8	1.9 / 96.9	1.3 / 129.1
Remainder	10.0 / -	10.6 / -	13.0 / -	97.1 / -	79.5 / -	33.6 / -	155.5 / -	118.3 / -	143.3 / -	105.5 / -	33.6 / -	42.9 / -	17.9 / -	0.3 / -
TOTAL	268.2 / 676.4	305.2 / 815.9	760.2 / 835.4	1050.5 / 1994.5	1446.2 / 3675.8	539.9 / 845.8	895.2 / 2003.6	1502.8 / 2903.7	2263.5 / 22145.1	2481.6 / 2472.4	73.3 / 203.0	356.7 / 1152.7	320.5 / 7522.5	24.5 / 171.5

basalt. The fauna was typical of rocky soils: goose barnacles (Scalpellum sp.), Sedentaria, bryozoans, sponges, hydroids, decapods (*Hymenodora frontalis*), bivalves (*Leda* sp.). The depauperation of the bottom-sample fauna at this station can evidently be explained by the complexity of the topography and of sedimentation in this area (Gershanovich 1963; Neiman 1963). The benthos biomass at stations of the south polygon was 40 g/m^2. The dominant group was foraminifers, but polychaetes, priapulids (*Priapulus caudatus*), sipunculids, and bivalves (*Thyasira* sp.) were also encountered. At station 25, Tanaidaceae of the genus *Apseudes* dominated in density, just as they did at station 24 of the west polygon. The trawl catch at station 4 showed a large quantity of glass sponges, polychaetes, cirripedes (*Littoscalpellum* sp.), isopods (*Arcturus* sp.), mysids (*Gnathophausia gigas*), decapods (*Munidospis beringana*), brittle stars, and sea cucumbers. At stations of the west polygon, there were many sponges, polychaetes, sea anemones, gastropods, Solenogastres and bivalves, scaphopods, brittle stars, sea cucumbers, side-swimmers, cumaceans, decapods, ascidians, and sea urchins of the genus *Brisaster*, the community of which is characteristic of the upper portion of the Shirshov Ridge (Filatova and Barsanova 1964).

Shallow stations of the north polygon were distinguished by the widest variety of bottom fauna, an appreciable biomass (190-1,100 g/m-^{2}), and a high density (3,500 organisms/m^2) of macrobenthic organisms. The polygon (stations 10, 11, 12, 15, 16) was characterized by communities of bivalves that were gathering detritophages: *Macoma calcarea, Nuculana pernula, Leionucula tenuis, Yoldia amigdalea* (Fig. 1). However, each station is characterized by the dominance of any one of the mollusks of this group. Accordingly, several different communities confined to oozy soils were distinguished. At the highest latitude stations (13, 14, 16), a community of the sea urchin *Strongilocentrotus droebachiensis* occurred on sandy, gravelly sediments with an admixture of silt. According to the data from 1981, the benthos fauna of this area also showed the presence of similar communities, including *S. droebachiensis*, noted earlier by Makarov (1937).

Based on a preliminary analysis, one can conclude that there is a similarity between the data on the distribution and abundance of the bottom fauna of the Bering Sea obtained during the 27th cruise of the RV *Akademik Shirshov* (1981) and the 37th cruise of the RV *Akademik Korolev* (1984). However, there are also differences. In the southern polygon we noted a community of foraminifers, and in the western polygon, a predominance of sponges and polychaetes, whereas in 1981, we observed communities of polychaetes and *Brisaster* in these areas. The *Brisaster* community was not observed at all in our investigations, nor were the following groups of animals found in the samples: stomatopods, cephalopods, and turbellarians. Our material showed the presence of xenophorans, leeches, and enteropneustans, which were absent from catches of the preceding cruise. We found pogonophores at only one station, as in the cruise of the RV *Akademik Shirshov*. Pogonophores in the Bering Sea had earlier been observed in appreciable quantities at great depths. It is possible that the observed differences in the structure of the bottom communities were due to the mosaic nature of the distribution of the bottom fauna and to the limited number of stations conducted in deepwater areas.

Since the work during the 1981 and 1984 expeditions aimed at studying the composition and nature of the distribution of zoobenthos in the Bering Sea was done in a relatively short time interval, the collected data supplement each other quite well. The new data obtained will later make it possible to assess the changes in the status of the benthic communities of the Bering Sea. The significant number of stations sampled in the third polygon makes it possible to compare the data obtained with data reported in the literature.

Neiman (1963) distinguishes the communities for this area: *Macoma calcarea, Leda pernula (Nuculana pernula), Nuccula tenuis (Leionucula tenuis), Yoldia hyperborea (Y. amigdalea), Ampelisca macrocephala, Ophiura sarsi, Sternapsis scutata,* and *Serripes groenlandicus.* Our studies confirmed the existence of four of these communities in the area (Fig. 1). The presence of species dominant in other indicated communities was not detected here. One of the organisms that we found here, *Strongilocentrotus droebachiensis*, had not been observed previously. It should be emphasized, however, that the areas studied by our

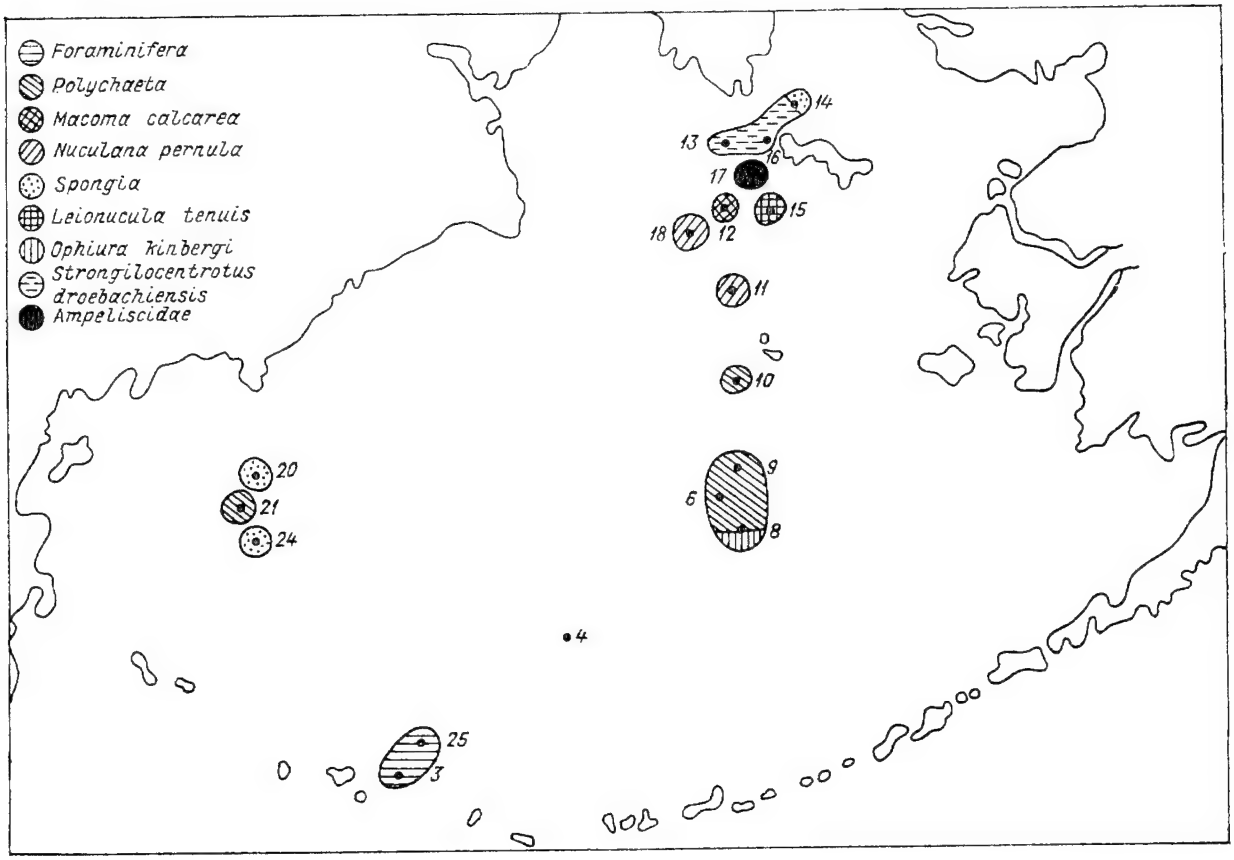

Fig. 1. Communities of benthic organisms at stations in the Bering Sea.

expedition and previous ones do not show complete agreement.

The literature contains information on the factors that have a decisive influence on the distribution of macrobenthos in the Bering Sea. Chief factors determining the trophic structure of the benthos are the hydrodynamics and the sediment texture (Tsyban et al. 1985). Sessile seston feeders inhabited places where the current action is strong and pebbles and large stones predominate in the sediments. In our investigations, the mass of sessile seston feeders was found in trawl catches conducted on the continental slope, on the slope of the Shirshov Ridge, and also at stations 13, 14, and 16 near St. Lawrence Island. Free-swimming seston feeders are found in areas of less dynamic activity and sediments with the predominance of the sandy and silt fraction. In our data, such conditions were noted in the third polygon, particularly at station 17, where free-swimming seston feeders of the family Ampeliscidae are dominant.

On silt sediments, the leading group consists of filtering detritus feeders. We found communities of filtering detritus feeders in the north polygon (stations 10, 11, 12, 15, 18). The soils at the stations were pelitic oozes with a hydrogen sulfide interlayer, indicating a weak hydrodynamics in this area.

Detritus feeders prefer even finer sediments, which are usually rich in organic matter. They

dominate in communities inhabiting depths greater than 100 m and sediments with a predominant pelitic silt fraction.

The nature of the biogeochemical processes determines the trophic niche of the fauna in this portion of the body of water. A good understanding of the trophic niche of the fauna in the species composition depends on the structure and distribution of the water masses.

Neiman (1963) established that the zones of a given zoogeographic complex coincide with the zones of contact with the bottom of various water masses. Neiman distinguishes four basic complexes—panarctic, arctic-boreal, low-arctic-boreal, and subarctic-boreal. Thus, one of the principal dominant species of food benthos, *Macoma calcarea*, is a panarctic species, and it reaches its highest biomass in waters with a subzero temperature.

The relationship of benthos to water masses is also partially traced in our data. For example, *Ophiura kinbergi* has been observed at three stations (8, 9, 21), differing in depths and location, but similar in soil and in water temperature (about +4°C).

In the third polygon, bivalves of the panarctic complex *M. calcarea, N. pernula, L. tenuis*, and *Y. amigdalea* are dominant: they yield the highest biomass (278 g/m^2) at a subzero water temperature. Also noted were a regular decrease in numbers and biomass and depletion of the quality composition of bottom-dwelling animals with depth.

Characteristics of Meiobenthos

In the studied areas of the Bering Sea, meiobenthos was represented by the categories of eumeiobenthos and pseudomeiobenthos. The first category includes foraminifers, nematodes, Harpacticoida, Kinorhyncha, ostracods, and Halacarida. Among animals of pseudomeiobenthos, representatives of Polychaeta, Oligochaeta, Sipuncula, and Mollusca (Gastropoda, Bivalvia) were found.

The basis of the meiobenthos population density consists of eumeiobenthos organisms: as a rule, they are the ones that produce a perceptible biomass of communities.

In the southern area, the meiobenthos was studied at only one of the stations (25), located at a depth of 4,000 m. Pelitic ooze with a small admixture of quartz sand had a yellowish hue owing to a large quantity of valves of diatomaceous algae, mainly representatives of the Coscinodiscacea family. The valves of the diatoms amounted to 25%-30% of the volume of the sample, and this made it possible to classify the bottom sediment as "diatomaceous ooze."

The quantitative content of diatoms on the bottom reflects the pattern characteristic of their distribution in the active layer of the ocean. In sediments of the Bering Sea, the content of *Coscinodiscus marginatus* Ehr. is close to 1 million bivalves/g (Zhuze et al. 1969). Here, in the area of the Aleutian upwelling (Tsyban et al. 1985), the large quantity of diatoms in the bottom sediments is due to high primary production.

Studies of bacteria in the sediment of deep-sea stations of the northwestern Pacific Ocean (Limberg-Ruban 1952) showed the presence of a large quantity of remnants of diatoms and a small number of bacteria. This discrepancy is explained by the decomposition of the cellular organic matter of diatoms on their way to the bottom, and thus mainly empty shells fall into the soil. Probably because of the low concentration of organic matter and microflora in the sediment, relatively small amounts of meiobenthos (24,500 organisms/m^2), producing a biomass of about 200 mg/m^2, are observed (Table 3).

The dominant group, amounting to about 85% of the population density and 8% of the meiobenthos biomass, is that of free-living nematodes.

In the area of Zhemchuzhnyy Canyon, station 6 is located at a depth of 3,171 m. A biotope of diatomaceous ooze is observed here, as in the case of the deepwater station discussed above. In a section of a core sample of the soil, interlayers of black ooze with an appreciable odor of hydrogen sulfide were noted, indicating the presence of organic matter in the bottom sediment and a weak hydrodynamics.

The meiobenthos here is dense; the population density of the organisms is 268,200 organisms/m^2 (Table 3). Of greatest importance in the formation of eumeiobenthos population density are nematodes, which account for over 87% of this index. The fraction of foraminifers in the total meiobenthos density is 12%.

With respect to the formation of the total biomass, a principal role is played by foraminifers (70%), while nematodes account for 25% of this characteristic.

At station 8 (depth, 146 m), a biotope of diatomaceous ooze was also observed with similar values of meiobenthos population density and biomass (Table 3).

As one moves northward (stations 10 and 11), the decrease in depths is associated with replacement of the biotopes and an increase in density of meiobenthos populations. The greatest development of meiobenthos was noted at station 11, 1×10^6 organisms/m^2, and the biomass is close to 2 g/m^2 (Table 3).

The northern region of the Bering Sea is characterized by the maximum quantitative development of meiobenthos. Here the population densities of the organisms reached 2.5×10^6 organisms/m^2, and the biomasses were 0.9-22 g/m^2.

The most appreciable difference in the quantitative development of meiobenthos was observed at stations 13 and 17. At the former, the quantitative characteristics of the meiobenthos were the lowest. At the latter station, an enormous development of meiobenthos was noted (2.2×10^6 organisms/m^2), yielding a biomass of 22.1 g/m^2. Such a high biomass is due to young bivalves (Table 3). This is the only station where such a huge stock of macrobenthos (45,700 organisms/m^2) is observed.

In spite of the neighboring locations of these stations and similar depths (55 and 61 m), the conditions differ markedly. The nature of the soil ranges from cobble roundstones with an admixture of ooze and detritus to oozy sand, enriched with detritus and algal fragments. The temperature of the bottom water at station 13 was 0.49°C, and at station 17, -1.63°C. The amounts of the nutrients, particularly silicon and nitrogen, differed appreciably.

For the meiobenthos communities at stations 12 and 17, a common feature was a sharp increase in the population density of foraminifers, which form a biomass of 2.8-4.3 g/m^2. These stations are confined to the oozy sand biotope with an admixture of detritus. Here, the quantitative indices of the nutrients (phosphorus, silicon, nitrogen) in the bottom layers of the water are the closest.

Thus, the northern region of the Bering Sea is distinguished by huge numbers of meiobenthos, primarily eumeiobenthos. The greatest development of the latter was noted south of St. Lawrence Island.

In the southwestern Bering Sea, at deep-sea stations 21 and 24 in the area of the Shirshov Ridge, the quantitative characteristics of meiobenthos are close to those of the eastern region. However, at these stations, which are confined to large depths (995-1,302 m), the population densities are 4-5 times those at station 20, which is located at a lesser depth (630 m). In addition, a distinctive feature of the meiobenthos at the latter station is the complete absence of representatives of pseudomeiobenthos (Table 3). Dominance is retained by nematodes.

Using data on the temperature, salinity, microflora, and nutrients at shallow stations of the northern polygon, we carried out an analysis of the distribution of macrobenthos and meiobenthos as a function of environmental factors.

We found that the biomass and density of the macrobenthos and meiobenthos decrease with increasing depth. These quantities reached their highest values at low temperature (close to 0°C and below). The changes in salinity in the area studied are insignificant and do not play any essential role in the distribution of benthos. The density maxima of foraminifers, amphipods, bivalves, and nematodes are observed at stations 12 and 17, where the phosphorus and silicon values are fairly high. The biomass and density of polychaetes, bivalves, and Harpacticoida coincide with the peak of the silicon content in the bottom water. The greatest quantity of nematodes was observed at stations 17 and 18, where a maximum of the bottom microflora of the northern polygon was noted.

Conclusions

1. The data obtained during the 37th cruise of the RV *Akademik Korolev* attest to the richness and variety of the bottom fauna of the Bering Sea and to the nonuniformity of its distribution.

2. The maximum biomass of macrozoobenthos in the areas studied is 1,100 g/m^2, and the maximum density, 3,500 organisms/m^2.

3. The first data on the meiobenthos of the Bering Sea areas studied have been obtained. Nematodes are most important in the formation of the quantitative characteristics of the meiobenthos. The dominant role of nematodes is seen in all the areas studied.

4. The greatest faunistic variety and abundance of macrobenthic and meiobenthic organisms are exhibited by communities of the north polygon; this is due to the variety of the composition of the soils, moderate depths, and predominance of the cold-water mass, causing the panarctic complex of bottom-dwelling animals in this region of the shelf to thrive.

5. Altogether, the data obtained on the distribution and abundance of the bottom fauna of the Bering Sea are similar to the results of earlier studies.

6. The zoobenthic distribution depends on various environmental factors: composition of the soil, the water mass adjacent to the bottom, the nutrient elements, and the bottom microflora. The distribution of individual groups of meiobenthos is related to specific groups of macrobenthos.

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Birds and Mammals

MARINE BIRD AND MAMMAL OBSERVATIONS FROM THE SECOND JOINT U.S.-U.S.S.R. EXPEDITION TO THE BERING SEA

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Introduction

Since Shuntov (1972) described the position of marine birds in the biological structure of the Bering Sea, there has been an increasing number of seabird studies in the area, most focusing on the southeastern Continental Shelf (Irving et al. 1970; Ogi and Tsujita 1973; Wahl 1978; Inverson et al. 1979; Hood and Calder 1981; Lensink and Forsell 1982; Schneider 1982; Schneider and Hunt 1982; Kinder et al. 1983; Woodby 1984; Schneider et al. 1986). Through these and other studies, it is becoming increasingly clear that the distribution of seabirds is not random but directly related to various environmental processes and parameters, both physical and biotic. Thus, as seabirds are an important and highly visible part of the apex of the food web, data on their distribution and abundance patterns are important in assessing and monitoring the health of the ecosystem.

The Second Joint U.S.-U.S.S.R. Expedition to the Bering Sea had a stated commitment to investigate the basic structural and functional indices of the biotic community over the entire Bering Sea. Towards this end, studies were conducted on the distribution and abundance of marine birds and mammals throughout the cruise.

Materials and Methods

Observations were made from the Soviet RV *Akademik Korolev* between 30 June and 27 July 1984. Density indices for marine birds and mammals were based on data from periodic transects (strip censuses) taken while the ship moved along a straight path at constant speed, usually about 20-27 km/h. A total of 220 transects were completed, plus an additional 26 counts taken while the ship was stationary (Table 1). Each transect was based on a 10-minute cruising period. All birds were counted forward from midship to the projected end of the transect (maximum of 3,000 m at 18.5 km/h), and laterally, on one side, to 300 m. The average area of observation was 1.35 km^2. Birds following the ship were recorded separately and not used for calculating indices of density. All observations were made from the flying bridge. Distances were estimated using a rangefinder developed by Heinemann (1981).

The expedition's cruise track was based on four principal study sites (polygons) selected and investigated in 1977 and in 1981 (see Fig. 1) and three stations along each of two transects connecting the south-east and east-north polygons. Since marine bird and mammal investigations rely heavily on a moving ship, the data reported here are not restricted to these areas but represent the cruise track of the vessel. The data have, however, been combined as closely as possible to correspond to the polygons where other research activities occurred (Table 1).

Observation conditions throughout much of the cruise were poor because of heavy seas and fog. This, combined with the fact that the ship frequently traveled between stations during periods of darkness, resulted in a relatively

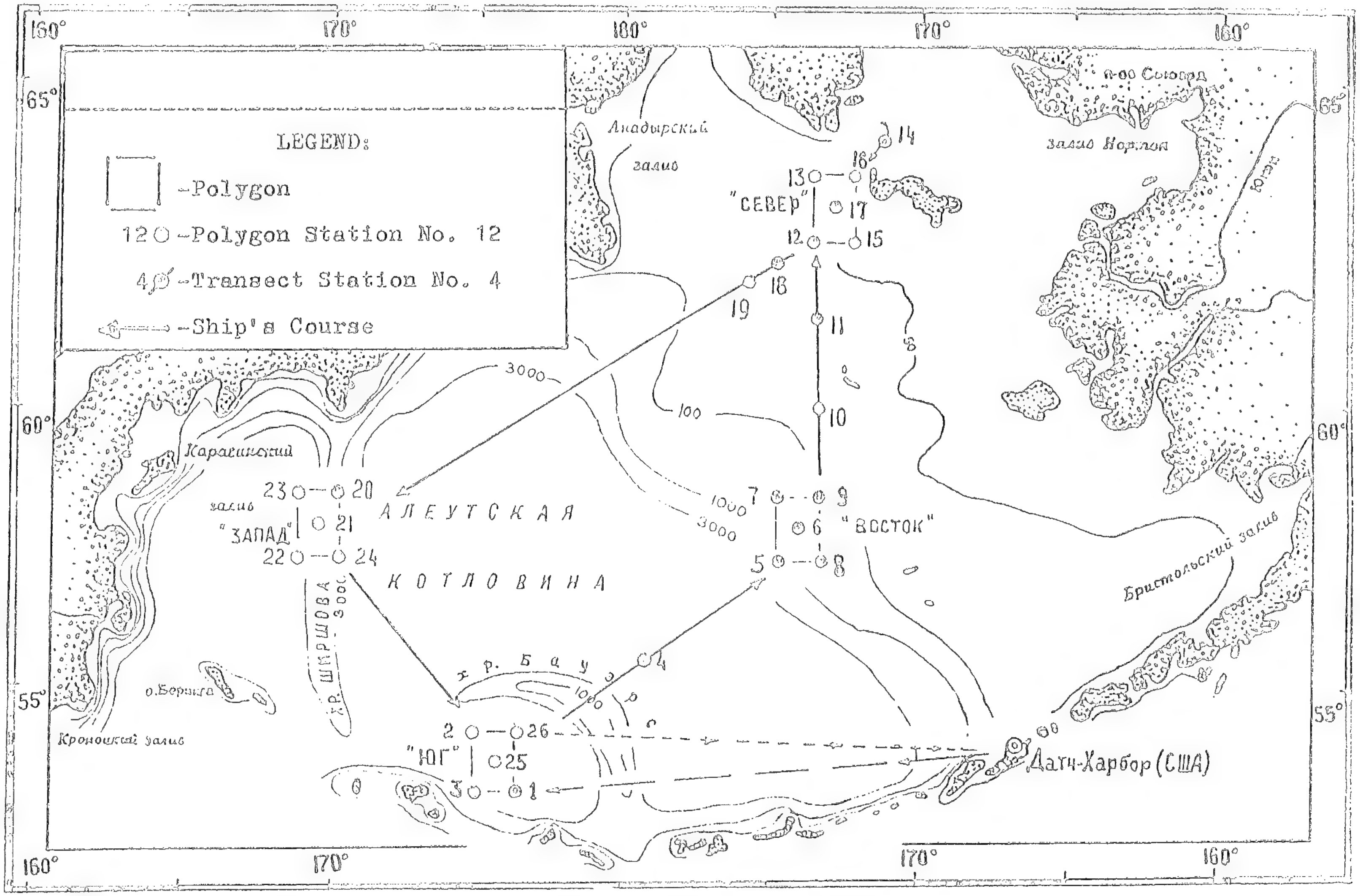

Fig. 1. Final program of the Second Joint U.S.-U.S.S.R. Expedition to the Bering Sea.

Table 1. *Marine bird and mammal logistics data.*

Date	Time (h)	Start position End position	Distance (nmi)	Heading (degrees)	Speed (kn) Coverage (km²/transect)	No. of counts
30 June						
	1230-1530	54°31.0'N, 171°55.0'W 54°31.0'N, 173°05.0'W	40.6	270	13.5 1.3	12
	1710-2040	54°31.0'N, 173°32.0'W 54°30.0'N, 175°00.0'W	50.1	269	14.6 1.4	8
01 July (Polygon 1)						
	1224-1524	54°10.4'N, 179°23.3'W 53°48.8'N, 178°19.2'W	43.3	119	14.4 1.3	15
	1658-1832	53°44.8'N, 178°11.9'E 53°32.6'N, 177°40.3'E	22.6	123	14.4 1.3	8
	2230-2240	53°16.8'N, 177°07.4'E	0	0	0	1
02 July (Polygon 1)						
	0845-1103	53°50.6'N, 176°20.4'E 54°02.8'N, 175°32.0'E	31.2	066	13.6 1.3	10
03 July						
	0800-2200	53°15.0'N, 175°20.0'E	0	0	0	5
04 July (Polygon 1)						
	1940-1950	53°52.5'N, 176°37.5'E	2.3	050	14.0 1.3	1
05 July						
	0900-0945	55°58.8'N, 179°53.4'E 56°04.2'N, 179°52.7'W	8.9	056	11.9 1.1	4
	1300-2100	56°32.2'N, 178°51.1'W	0	0	0	8

Table 1. *Continued.*

Date Time (h)	Start position End position	Distance (nmi)	Heading (degrees)	Speed (kn) Coverage (km²/transect)	No. of counts
06 July					
0800-1400	56°43.8'N, 178°32.0'W	0	0	0	6
07 July (Polygon 2)					
0700-1400	57°26.6'N, 175°57.0'W	0	0	0	8
1500-2000	57°23.6'N, 175°45.9'W	0	0	0	5
2200-2300	57°30.7'N, 175°24.6'W 57°45.5'N, 175°20.0'W	14.9	010	14.9 1.4	6
08 July (Polygon 2)					
0930-1400	57°57.5'N, 175°00.3'W	0	0	0	3
1820-1910	57°53.3'N, 174°51.8'W 58°00.2'N, 175°05.5'W	9.9	314	11.9 1.1	5
09 July (Polygon 2)					
0758-0848	58°14.4'N, 175°33.8'W 58°24.2'N, 175°48.4'W	12.3	322	14.7 1.36	3
1145-1530	58°29.8'N, 176°05.7'W	0	0	0	4
1650-2100	58°25.2'N, 175°52.7'W 57°42.4'N, 174°25.6'W	63.1	132	15.1 1.4	19
10 July (Polygon 2)					
1000-1015	57°26.1'N, 173°41.6'W	0	0	0	1
1229-1500	57°47.2'N, 173°44.2'W 58°24.5'N, 173°57.3'W	38.1	350	15.2 1.4	9
1730-2030	58°35.0'N, 174°00.0'W	0	0	0	2

Table 1. *Continued.*

Date	Time (h)	Start position End position	Distance (nmi)	Heading (degrees)	Speed (kn) Coverage (km²/transect)	No. of counts
11 July						
	0800-1330	60°00.8'N, 173°57.3'W	0	0	0	3
	1355-1540	60°00.7'N, 174°04.7'W 60°25.0'N, 174°06.8'W	24.4	355	14.0 1.3	9
	1625-1845	60°25.4'N, 174°08.7'W 60°58.4'N, 173°57.1'W	33.6	010	14.4 1.3	10
	2200-2215	61°30.6'N, 173°40.3'W	0	0	0	1
12 July (Polygon 3)						
	0815-0922	62°18.0'N, 173°32.7'W 62°33.9'N, 173°31.4'W	16.5	002	14.8 1.4	6
	1015-1115	62°38.5'N, 173°32.5'W 62°52.6'N, 173°30.0'W	14.2	005	14.2 1.3	6
	1300-1630	63°04.9'N, 173°27.7'W	0	0	0	3
	1812-2202	63°06.1'N, 173°34.0'W 64°02.6'N, 173°27.8'W	55.9	003	14.6 1.4	16
13 July (Polygon 3)						
	0800-1330	63°59.5'N, 173°28.9'W	0	0	0	3
	1335-1520	63°56.9'N, 173°07.3'W 64°09.3'N, 172°20.7'W	23.6	059	13.5 1.3	8
	1615-1720	64°12.7'N, 172°06.5'W 64°20.0'N, 171°31.0'W	17.0	066	15.7 1.5	6
	2100-2300	64°20.0'N, 171°31.0'W	0	0	0	2
14 July (Polygon 3)						
	0900-1330	62°58.5'N, 172°29.6'W	0	0	0	3

Table 1. *Continued.*

Date	Time (h)	Start position End position	Distance (nmi)	Heading (degrees)	Speed (kn) Coverage (km²/transect)	No. of counts
	1428-1510	62°58.7'N, 172°22.9'W 63°07.5'N, 171°23.9'W	8.7	357	12.4 1.2	5
	1613-1720	63°14.5'N, 172°25.3'W 63°29.3'N, 172°26.4'W	14.7	355	13.2 1.2	6
	1720-1851	63°29.3'N, 172°26.4'W 63°50.9'N, 172°28.9'W	22.0	357	14.5 1.4	7
	2000-2130	63°58.0'N, 172°28.5'W	0	0	0	2
15 July						
	0900-1800	63°26.1'N, 172°52.4'W	0	0	0	3
16 July (Polygon 3)						
	1030-1630	62°49.1'N, 174°27.8'W	0	0	0	3
	1704-1820	62°42.7'N, 174°29.5'W 62°37.4'N, 175°05.7'W	17.3	252	13.6 1.3	7
17 July						
	0830-1300	62°26.1'N, 175°14.6'W	0	0	0	3
19 July						
	1500-2330	58°33.6'N, 170°27.6'E	0	0	0	5
20 July						
	1000-2030	58°00.0'N, 170°27.6'E	0	0	0	7
21 July (polygon 4)						
	1305-1445	57°53.8'N, 169°47.8'E 57°31.7'N, 169°31.4'E	23.8	202	14.3 1.3	9
	1630-2130	57°30.0'N, 169°30.0'E	0	0	0	4

Table 1. *Continued.*

Date	Time (h)	Start position End position	Distance (nmi)	Heading (degrees)	Speed (kn) Coverage (km²/transect)	No. of counts
22-23 July (Polygon 4)						
	0900-1630	58°30.0'N, 169°30.0'E	0	0	0	7
	2310-0006	58°29.0'N, 169°55.9'E 58°16.5'N, 170°02.2'E	12.6	166	13.5 1.3	5
23 July						
	0800-2100	57°28.0'N, 170°33.8'E	0	0	0	8
24 July						
	0851-0940	55°47.5'N, 173°22.1'E 55°39.9'N, 173°33.2'E	9.7	139	11.8 1.1	3
	1042-1505	55°37.2'N, 173°36.1'E 54°47.4'N, 174°42.7'E	62.7	142	14.9 1.4	11
25 July						
	0900-2200	53°43.8'N, 176°21.5'E	0	0	0	11
26 July						
	0900-2100	54°12.3'N, 177°06.2'E	0	0	0	7
27 July						
	1300-1630	54°31.8'N, 178°55.9'E	0	0	0	4
	1954-2101	54°29.5'N, 178°04.7'W 54°29.8'N, 177°36.7'W	16.3	088	14.6 1.4	6
28 July						
	1000-2200	54°30.5'N, 173°18.4'W	0	0	0	5

small data base being accumulated. A total of 223 10-minute transects was completed covering a linear distance of 984.6 km and a surveyed area of 295.3 km^2.

Data have been analyzed on the basis of three depth ranges of the total Bering Sea: Continental Shelf (0-199 m), continental slope (200-1,999 m), and basin (2,000 + m); and four polygons: P1 (South), P2 (East), P3 (North), and P4 (West).

Results

Thirty-two species of birds and ten species of mammals were recorded during the cruise (Table 2). The most frequently observed species was the northern fulmar (*Fulmarus glacialis*), occurring in 60.5% of all transects. Thick-billed murres (*Uria lomvia*), common murres (*Uria aalge*), and fork-tailed storm-petrels (*Oceanodroma furcata*) followed as the next most frequently observed species. If unidentified murres are equally divided into common and thick-billed, then these two species and the northern fulmar were the most abundant species throughout the Bering Sea, with overall density indices between 1.43-1.49 birds/km^2. The only other species with an overall density index exceeding 1.0 was the least auklet (*Aethia pusilla*), at 1.05 birds/km^2. Dall's porpoise (*Phocenoides dalli*) was by far the most abundant and frequently observed mammal, occurring in 3.1% of all transects and having an overall density index of 0.08 mammals/km^2.

All but one of the birds and mammals recorded during this cruise are regular inhabitants of the Bering Sea and have been recorded in most other studies of the area. The exception was a Swinhoe's storm-petrel (*Oceanodroma monorhis*) that, had we been able to collect the specimen, would have been the first confirmed record for the Bering Sea.

In general, highest total bird densities occur over the Continental Shelf near major breeding colonies (Fig. 2), principally a result of the contribution of large numbers of alcids (Tables 3-9). Fulmars (Fig. 3), kittiwakes (*Rissa* sp.) (Fig. 4), and jaegers (*Stercorarius* sp.) (Fig. 5) were widespread with only slightly higher densities in shallower waters. Shearwaters (*Puffinus* sp.) (Fig. 6), storm-petrels (*Oceanodroma* sp.) (Fig. 7), albatrosses (*Diomedia* sp.), and mottled petrels (*Pterodroma inexpectata*) are clearly birds of deep waters, while murres (Fig. 8), auklets (*Aethia* sp.) (Fig. 9), and puffins (*Fratercula* sp.) (Fig. 10) are birds of shallow waters. This same pattern is reflected by densities and occurrences in the four polygon areas (Figs. 11-19); that is, the highest total density occurred in polygon 3 (Table 8), which was just west of St. Lawrence Island, a major nesting area for alcids, and a relatively short distance north of St. Mathew Island, a major nesting area for both alcids and northern fulmars (Sowls et al. 1978).

Species Listing

Laysan albatross. Regular in small numbers throughout deep-water areas (1,800-3,900 m) of the Bering Sea. The northernmost records were a single bird at 58°00.0'N, 170°00.0'E and another at 57°23.6'N, 175°45.9'W.

Northern fulmar. The most abundant and frequently observed species throughout the cruise. Dark-phase birds predominated in the south, and light-phase birds predominated in the north. None of the former were found in polygon 3 and none of the latter were found in polygon 1. Dark-phase birds predominated in polygon 4 and made up about 56% of those observed in polygon 3, where the largest numbers of the cruise were found during station counts over the continental slope northeast of the Pribilof Islands. The high frequency of occurrence (Table 2) for this species may in part be related to their ship-following and ship-investigating habits.

Mottled petrel. One bird was observed on 25 July at 53°43.8'N, 176°21.5'E over a water depth of 3,900 m.

Table 2. *Marine birds and mammals observed during the Second Joint U.S.-U.S.S.R. Expedition to the Bering Sea.*

Code	Species	Density Index[a]	Frequency Index[b]
LAAL	Laysan albatross (*Diomedea immutabilis*)	0.02	03.1
NOFU	Northern fulmar (*Fulmarus glacialis*)	1.49	60.5
MOPE	Mottled petrel (*Pterodroma inexpectata*)	+[c]	00.0
SOSH	Sooty shearwater (*Puffinus griseus*)	0.05	02.2
STSH	Short-tailed shearwater (*Puffinus tenuirostris*)	0.38	06.7
UNSH	Shearwater sp. (*Puffinus* sp.)	0.11	07.6
FTSP	Fork-tailed storm-petrel (*Oceanodroma furcata*)	0.49	27.8
LESP	Leach's storm petrel (*Oceanodroma leucorhoa*)	+[c]	00.0
SWSP	Swinhoe's storm-petrel (*Oceanodroma monorhis*)	+[c]	00.4
UNSP	Storm-petrel sp. (*Oceanodroma* sp.)	0.08	03.6
PECO	Pelagic cormorant (*Phalacrocorax pelagicus*)	0.01	00.4
HADU	Harlequin duck (*Histronicus histronicus*)	+[c]	00.0
RUTU	Ruddy turnstone (*Arenaria interpres*)	+[c]	00.0
UNPH	Phalarope sp. (*Phalaropus* sp.)	0.02	01.3
POJA	Pomarine jaeger (*Stercorarius pomarinus*)	0.06	05.8
PAJA	Parasitic jaeger (*Stercorarius parasiticus*)	0.01	01.3
LTJA	Long-tailed jaeger (*Stercorarius longicaudus*)	+[c]	00.0
UNJA	Jaeger sp. (*Stercorarius* sp.)	+[c]	00.4
HEGU	Herring gull (*Larus argentatus*)	0.01	01.8
SBGU	Slaty-backed gull (*Larus schistisagus*)	+[c]	00.0
GWGU	Glaucous-winged gull (*Larus glaucescens*)	0.01	00.9
BLKI	Black-legged kittiwake (*Rissa tridactyla*)	0.30	14.3
RLKI	Red-legged kittiwake (*Rissa brevirostris*)	0.02	01.8
UNKI	Kittiwake sp. (*Rissa* sp.)	0.04	00.9
SAGU	Sabine's gull (*Xema sabini*)	+[c]	00.0
UNITE	Tern sp. (*Sterna* sp.)	+[c]	00.0
COMU	Common murre (*Uria aalge*)	0.26	13.9
TBMU	Thick-billed murre (*Uria lomvia*)	0.32	15.7
UNMU	Murre (*Uria* sp.)	2.35	38.6
PIGU	Pigeon guillemot (*Cepphus columba*)	0.04	400.4
ANMY	Ancient murrelet (*Synthliboramphus antiguus*)	0.01	00.4
UNML	Murrelet sp. (*Brachyramphus* sp.)	0.01	00.4
PAAU	Parakeet auklet (*Cyclorrhynchus psittacula*)	0.15	07.6
LEAU	Least auklet (*Aethia pusilla*)	1.05	07.6
CRAU	Crested auklet (*Aethia cristatella*)	0.03	02.2
TUPU	Tufted puffin (*Fratercula cirrhata*)	0.13	11.7
HOPU	Horned puffin (*Fratercula corniculata*)	0.05	05.4
UNBI	Bird sp.	0.04	03.1
Total Birds		7.59	98.7

Table 2. *Continued.*

Code	Species	Density Index[a]	Frequency Index[b]
DAPO	Dall's porpoise (*Phocoenoides dalli*)	0.08	03.1
HAPO	Harbor porpoise (*Phocoena phocoena*)	0.01	00.4
STSL	Steller's sea lion (*Eumetopias jubatus*)	+[c]	00.0
HASE	Harbor seal (*Phoca vitulina richardsi*)	+[c]	00.0
NOFS	Northern fur seal (*Callorhinus ursinus*)	+[c]	00.4
UNSE	Seal sp.	+[c]	00.0
WALR	Walrus (*Odobenus rosmarus*)	+[c]	00.4
SEWH	Sei whale (*Balaenoptera borealis*)	+[c]	00.0
MIWH	Minke whale (*Balaenoptera acutorostrata*)	+[c]	00.0
FIWH	Fin whale (*Balaenoptera physalus*)	+[c]	00.0
KIWH	Killer whale (*Orcinus orca*)	+[c]	00.0
UNWH	Whale sp.	+[c]	00.0
Total Mammals		0.10	04.3

[a]Density index = animals/square kilometer/transect
[b]Frequency = percent of total 10-minute transects on which species was recorded.
[c]Present but density <0.01 animals/km^2.

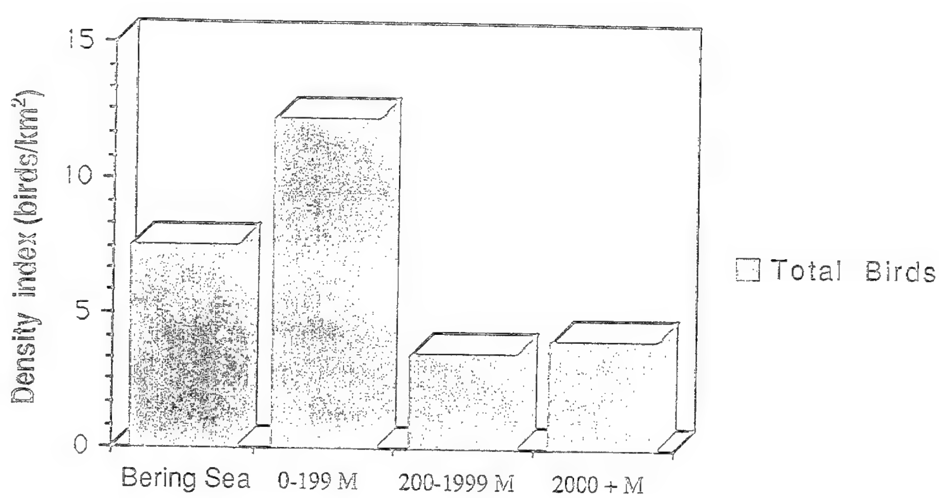

Fig. 2. Total birds by depth in the Bering Sea.

Table 3. *Density indices for birds and mammals over shelf water (<200 m) of the Bering Sea.*

Species	No./km^2	+ 2SE	% Total
Northern fulmar	1.96	1.00	16.5
Short-tailed shearwater	0.01	0.02	0.1
Shearwater sp.	0.01	0.02	0.1
Fork-tailed storm-petrel	0.05	0.06	0.4
Leach's storm-petrel	+[a]	+[a]	+[a]
Storm-petrel sp.	0.01	0.02	0.1
Cormorant sp.	+[a]	+[a]	+[a]
Shorebird sp.	0.01	0.02	0.1
Phalarope sp.	0.01	0.02	0.1
Pomarine jaeger	0.03	0.04	0.3
Parasitic jaeger	0.02	0.02	0.1
Slaty-backed gull	+[a]	+[a]	+[a]
Glaucous-winged gull	0.01	0.02	0.1
Herring gull	0.03	0.04	0.3
Black-legged kittiwake	0.39	0.46	3.4
Tern sp.	+[a]	+[a]	+[a]
Common murre	0.59	0.28	4.8
Thick-billed murre	0.71	0.32	5.7
Murre sp.	5.23	1.44	41.6
Pigeon guillemot	0.09	0.14	0.8
Murrelet sp.	0.03	0.06	0.3
Parakeet auklet	0.35	0.20	2.9
Crested auklet	0.05	0.06	0.4
Least auklet	2.31	1.46	19.1
Horned puffin	0.10	0.06	0.8
Tufted puffin	0.22	0.12	1.9
Bird sp.	0.02	0.02	0.2
Total birds	12.24	2.44	100.0
Harbor seal	+[a]	+[a]	+[a]
Steller's sea lion	+[a]	+[a]	+[a]
Walrus	+[a]	+[a]	16.7
Dall's porpoise	0.02	0.04	33.3
Minke whale	+[a]	+[a]	+[a]
Fin whale	+[a]	+[a]	+[a]
Mammal sp.	0.02	0.04	50.0
Total mammals	0.04	0.06	100.0

[a]Present but density <0.01 animals/km^2.

Table 4. *Density indices for birds and mammals over slope waters (200-1,999 m) of the Bering Sea.*

Species	No./km²	+ 2SE	% Total
Laysan albatross	0.03	0.06	0.8
Northern fulmar	0.78	0.40	22.5
Sooty shearwater	0.40	0.50	10.0
Short-tailed shearwater	0.09	0.18	2.5
Fork-tailed storm-petrel	1.01	0.70	29.2
Storm-petrel sp.	0.14	0.14	4.2
Ruddy turnstone	+[a]	+[a]	+[a]
Shorebird sp.	0.12	0.14	3.3
Pomarine jaeger	0.03	0.06	0.8
Long-tailed jaeger	+[a]	+[a]	+[a]
Jaeger sp.	0.03	0.06	0.8
Sabine's gull	+[a]	+[a]	+[a]
Black-legged kittiwake	0.21	0.20	5.8
Red-legged kittiwake	+[a]	+[a]	+[a]
Common murre	0.03	0.06	0.8
Crested auklet	0.09	0.12	2.5
Least auklet	0.32	0.64	9.2
Horned puffin	+[a]	+[a]	+[a]
Bird sp.	0.26	0.30	7.5
Total birds	3.52	1.16	100.0
Dall's porpoise	0.26	0.38	100.0
Killer whale	+[a]	+[a]	+[a]
Minke whale	+[a]	+[a]	+[a]
Total mammals	0.26	0.38	100.0

[a]Present but density <0.01 animals/km^2.

Table 5. *Density indices for birds and mammals over basin waters (>1,999 m) of the Bering Sea.*

Species	No./km²	+ 2SE	% Total
Laysan albatross	0.04	0.04	0.9
Northern fulmar	1.21	0.26	29.8
Sooty shearwater	0.02	0.04	0.6
Short-tailed shearwater	0.82	1.26	20.2
Shearwater sp.	0.24	0.14	6.0
Mottled petrel	+[a]	+[a]	+[a]
Fork-tailed storm-petrel	0.80	0.30	20.0
Leach's storm-petrel	+[a]	+[a]	+[a]
Swinhoe's storm-petrel	0.01	0.02	0.2
Storm-petrel sp.	0.15	0.10	3.6
Pelagic cormorant	0.01	0.02	0.4
Phalarope sp.	0.04	0.06	1.1
Pomarine jaeger	0.07	0.06	1.7
Parasitic jaeger	0.02	0.04	0.4
Glaucous-winged gull	0.01	0.02	0.4
Black-legged kittiwake	0.24	0.18	5.6
Red-legged kittiwake	0.04	0.04	0.9
Kittiwake sp.	0.10	0.18	2.4
Thick-billed murre	0.03	0.02	0.8
Murre sp.	0.10	0.08	4.0
Ancient murrelet	0.01	0.02	0.4
Horned puffin	0.01	0.02	0.2
Tufted puffin	0.08	0.06	1.9
Bird sp.	0.01	0.02	0.2
Total birds	4.06	1.42	100.0
Northern fur seal	0.01	0.02	4.5
Steller's sea lion	+[a]	+[a]	+[a]
Seal sp.	+[a]	+[a]	+[a]
Dall's porpoise	0.14	0.12	81.8
Harbor porpoise	0.02	0.04	9.1
Minke whale	+[a]	+[a]	+[a]
Sei whale	+[a]	+[a]	+[a]
Whale sp.	0.01	0.02	4.5
Total mammals	0.18	0.13	100.0

[a]Present but density >0.01 animals/km².

Table 6. *Density indices for birds and mammals over Bower's Basin (polygon 1).*

Species	No./km^2	+ 2SE	% Total
Laysan albatross	0.09	0.08	1.6
Northern fulmar	1.23	0.42	23.1
Sooty shearwater	+[a]	+[a]	+[a]
Short-tailed shearwater	2.15	3.68	38.5
Shearwater sp.	0.45	0.38	3.1
Mottled petrel	+[a]	+[a]	+[a]
Fork-tailed storm-petrel	1.07	0.52	20.2
Swinhoe's storm-petrel	0.02	0.26	0.4
Storm-petrel sp.	0.13	0.12	2.4
Pelagic cormorant	0.04	0.50	0.8
Phalarope sp.	0.06	0.74	1.2
Pomarine jaeger	0.06	0.42	1.2
Glaucous-winged gull	+[a]	+[a]	+[a]
Black-legged kittiwake	+[a]	+[a]	+[a]
Murre sp.	0.11	0.18	2.0
Horned puffin	+[a]	+[a]	+[a]
Tufted puffin	0.02	0.04	0.4
Total birds	5.44	3.72	100.0
Dall's porpoise	0.20	0.29	100.0
Seal sp.	+[a]	+[a]	+[a]
Total mammals	0.20	0.29	100.0

[a]Present but density <0.01 animals/km^2.

Table 7. *Density indices for birds and mammals over Zhemchug Canyon (polygon 2).*

Species	No./km^2	+ 2SE	% Total
Laysan albatross	+[a]	+[a]	+[a]
Northern fulmar	1.06	0.32	35.3
Short-tailed shearwater	0.12	0.14	4.1
Shearwater sp.	0.04	0.05	1.2
Fork-tailed storm-petrel	0.62	0.34	20.6
Leach's storm-petrel	+[a]	+[a]	+[a]
Storm-petrel sp.	0.09	0.08	2.9
Pomarine jaeger	0.08	0.09	2.9
Jaeger sp.	0.02	0.04	0.6
Glaucous-winged gull	0.03	0.06	1.2
Black-legged kittiwake	0.37	0.12	11.2
Red-legged kittiwake	+[a]	+[a]	+[a]
Kittiwake sp.	0.02	0.04	0.6
Common murre	0.02	0.04	0.6
Thick-billed murre	0.05	0.06	1.8
Murre sp.	0.03	0.03	1.2
Crested auklet	0.05	0.08	1.8
Least auklet	0.19	0.40	6.5
Tufted puffin	0.02	0.04	0.6
Total birds	3.02	0.98	100.0
Steller's sea lion	+[a]	+[a]	+[a]
Sei whale	+[a]	+[a]	+[a]
Dall's porpoise	0.17	0.11	100.0
Total mammals	0.17	0.11	100.0

[a]Present but density <0.01 animals/km^2.

Table 8. *Density indices for birds and mammals over the St. Lawrence Island shelf (polygon 3).*

Species	No./km^2	+ 2SE	% Total
Northern fulmar	2.68	1.42	23.7
Phalarope sp.	0.01	0.02	0.1
Pomarine jaeger	0.05	0.06	0.4
Parasitic jaeger	0.02	0.04	0.2
Slaty-backed gull	+[a]	+[a]	+[a]
Herring gull	0.05	0.04	0.4
Black-legged kittiwake	0.17	0.12	1.5
Tern sp.	+[a]	+[a]	+[a]
Common murre	0.46	0.34	3.9
Thick-billed murre	0.41	0.24	3.5
Murre sp.	5.95	1.98	49.0
Pigeon guillemot	0.02	0.04	0.2
Parakeet auklet	0.40	0.28	3.6
Crested auklet	0.02	0.04	0.2
Least auklet	1.24	1.02	11.1
Horned puffin	0.07	0.06	0.6
Tufted puffin	0.19	0.10	1.7
Bird sp.	0.01	0.02	0.1
Total birds	11.77	2.88	100.0
Harbor seal	+[a]	+[a]	+[a]
Steller's sea lion	+[a]	+[a]	+[a]
Walrus	0.01	0.02	25.0
Minke whale	+[a]	+[a]	+[a]
Mammal sp.	0.03	0.06	75.0
Total mammals	0.04	0.06	100.0

[a]Present but density <0.01 animals/km^2.

Table 9. *Density indices for birds and mammals over Shirshov Ridge (polygon 4).*

Species	No./km^2	+ 2SE	% Total
Laysan albatross	+[a]	+[a]	+[a]
Northern fulmar	0.39	0.28	20.0
Short-tailed shearwater	0.32	0.38	17.1
Sooty shearwater	0.69	0.86	34.3
Fork-tailed storm-petrel	0.06	0.12	2.9
Harlequin duck	+[a]	+[a]	+[a]
Ruddy turnstone	+[a]	+[a]	+[a]
Phalarope sp.	0.16	0.32	8.6
Pomarine jaeger	0.06	0.12	2.9
Long-tailed jaeger	+[a]	+[a]	+[a]
Sabine's gull	+[a]	+[a]	+[a]
Black-legged kittiwake	0.11	0.16	5.7
Red-legged kittiwake	+[a]	+[a]	+[a]
Tufted puffin	0.16	0.24	8.6
Total birds	1.94	0.78	100.0
Dall's porpoise	+[a]	+[a]	+[a]
Total mammals	+[a]	+[a]	+[a]

[a]Present but density <0.01 animals/km^2.

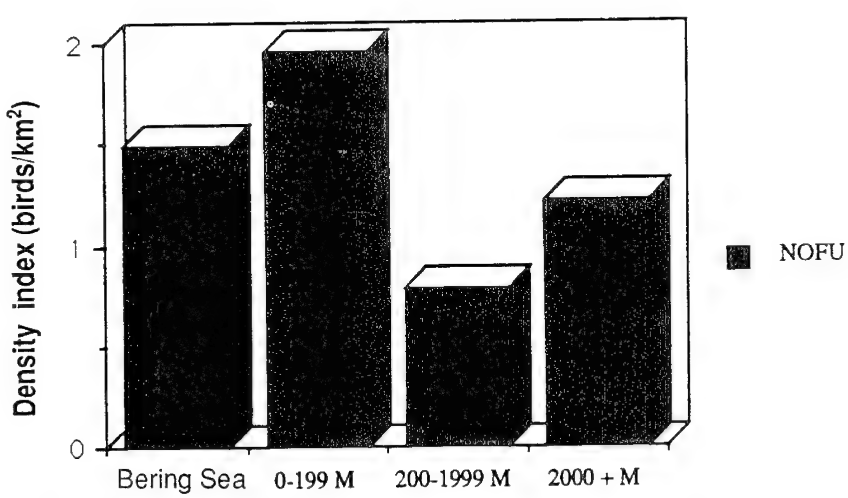

Fig. 3. Northern fulmars by depth in the Bering Sea.

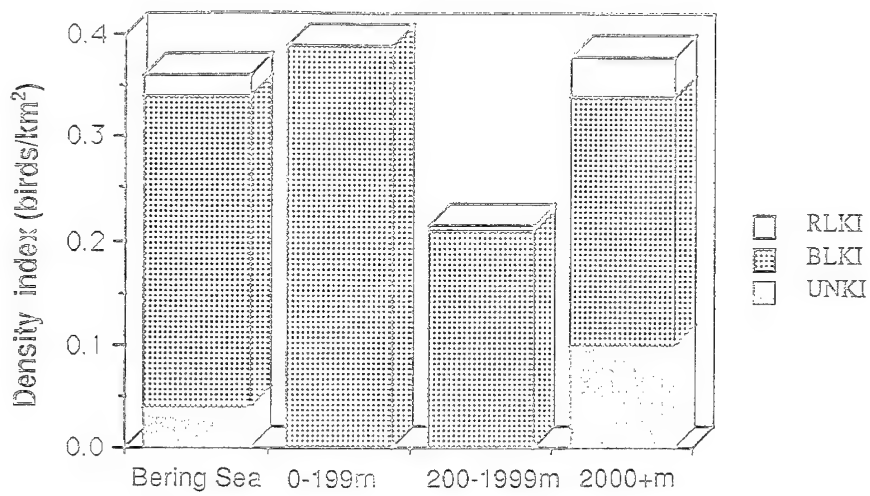

Fig. 4. Kittiwakes by depth in the Bering Sea. (See Table 2 for codes.)

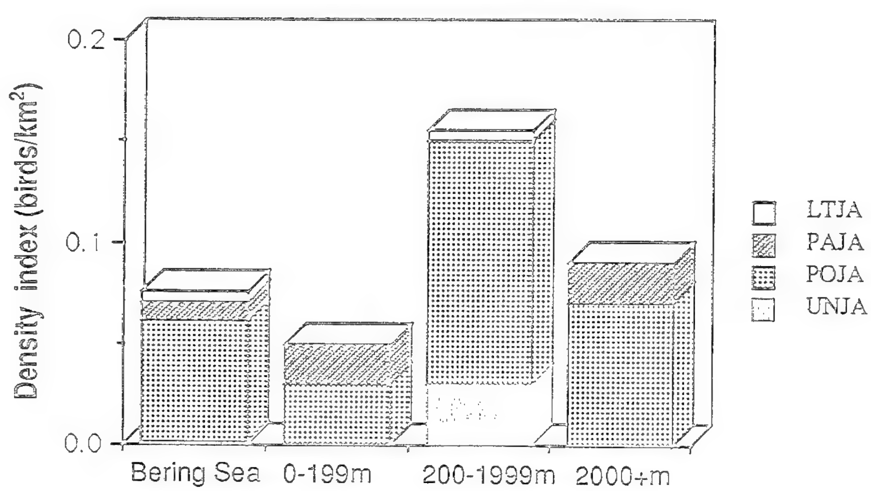

Fig. 5. Jaegers by depth in the Bering Sea. (See Table 2 for codes.)

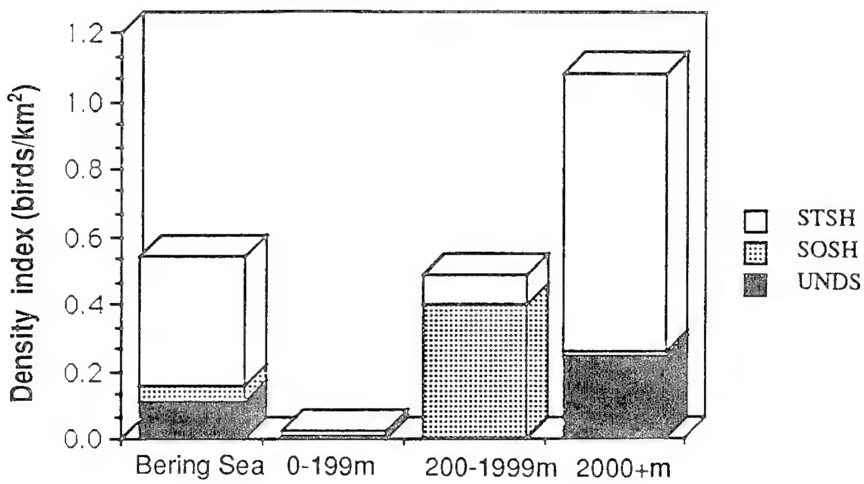

Fig. 6. Shearwaters by depth in the Bering Sea. (See Table 2 for codes.)

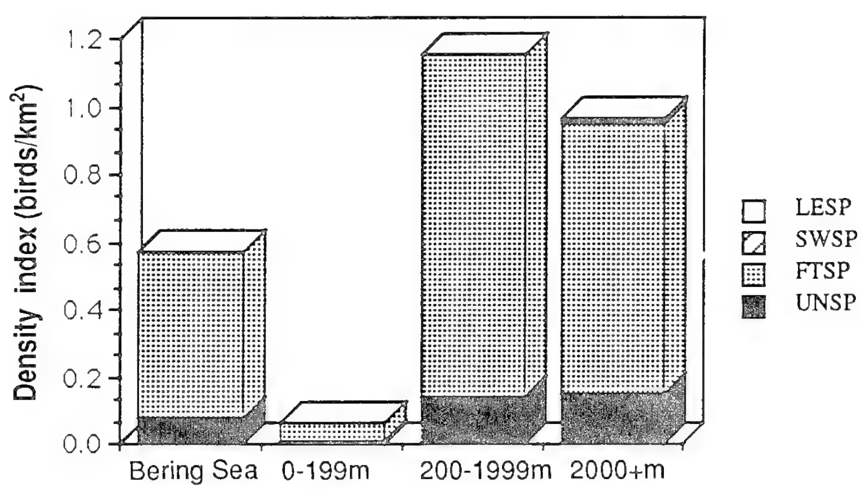

Fig. 7. Storm-petrels by depth in the Bering Sea. (See Table 2 for codes.)

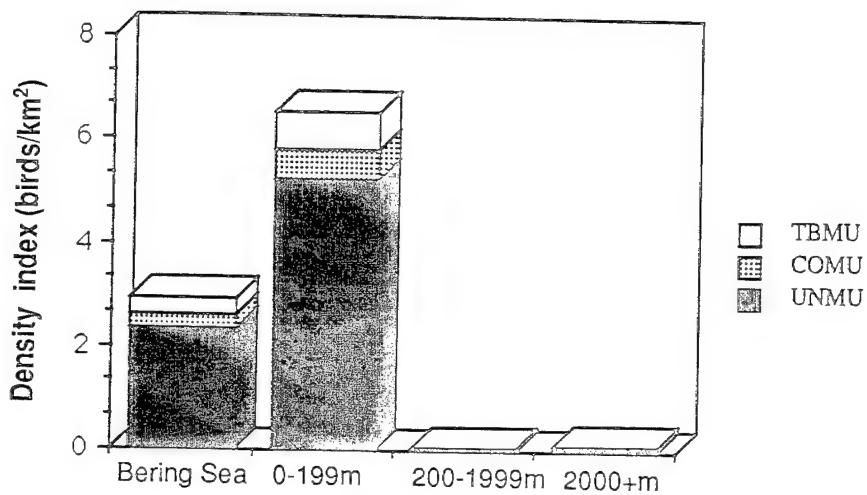

Fig. 8. Murres by depth in the Bering Sea. (See Table 2 for codes.)

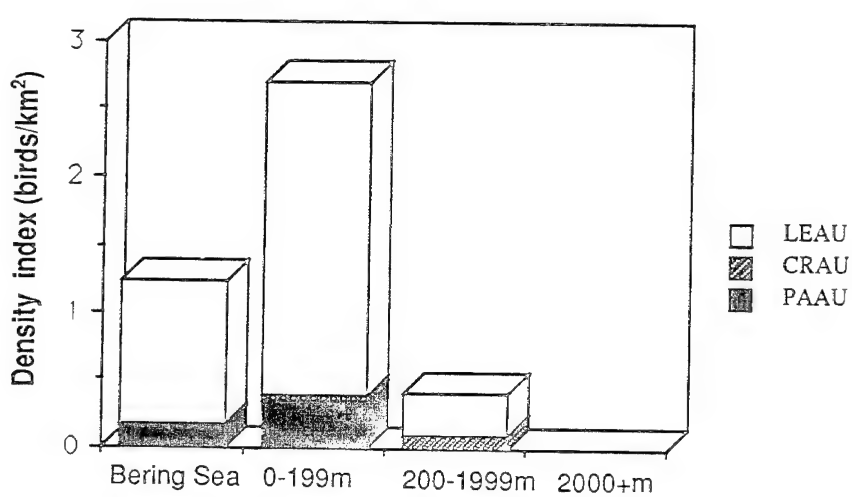

Fig. 9. Auklets by depth in the Bering Sea. (See Table 2 for codes.)

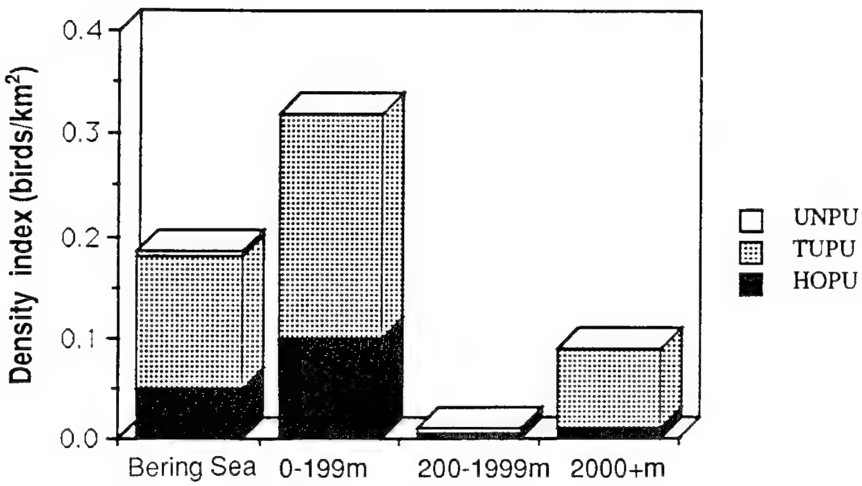

Fig. 10. Puffins by depth in the Bering Sea. (See Table 2 for codes.)

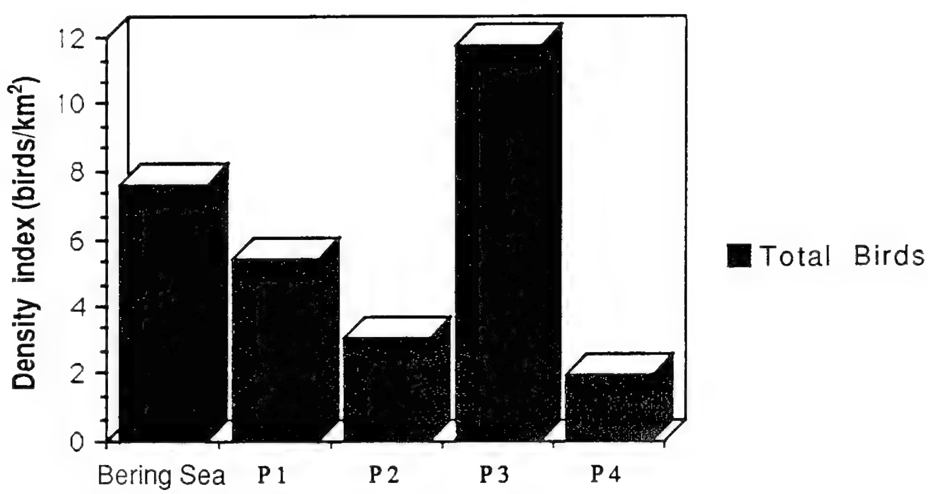

Fig. 11. Total birds by polygon in the Bering Sea.

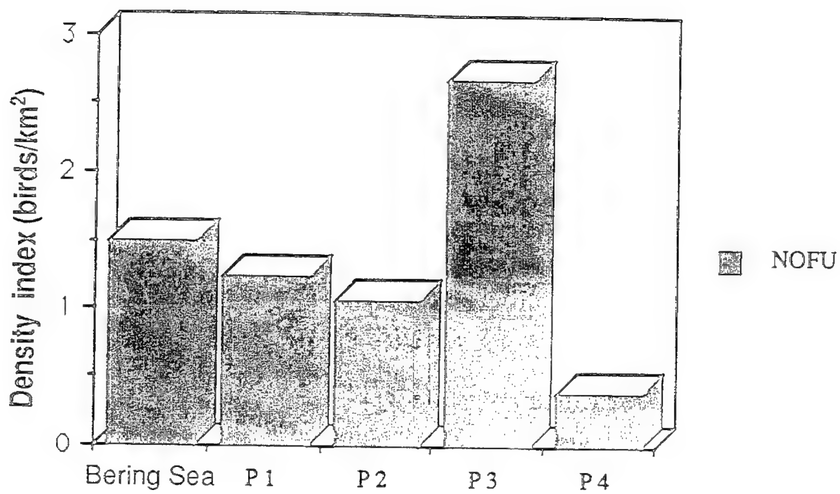

Fig. 12. Northern fulmars by polygon in the Bering Sea.

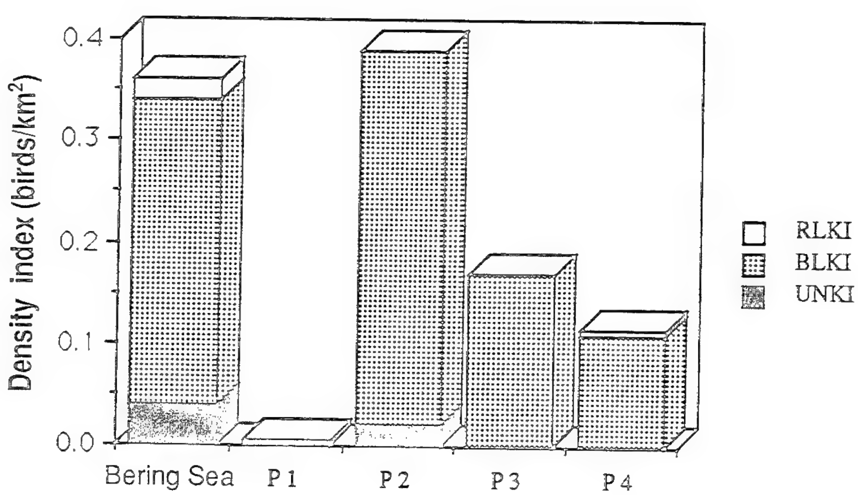

Fig. 13. Kittiwakes by polygon in the Bering Sea. (See Table 2 for codes.)

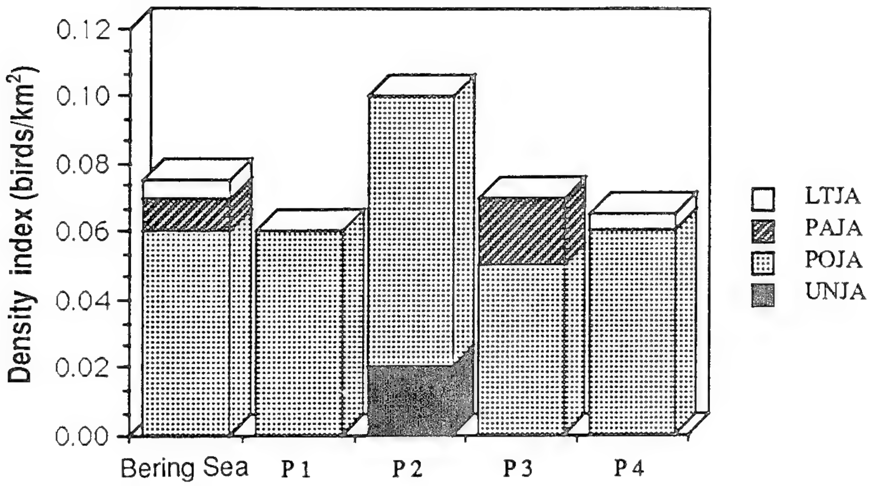

Fig. 14. Jaegers by polygon in the Bering Sea. (See Table 2 for codes.)

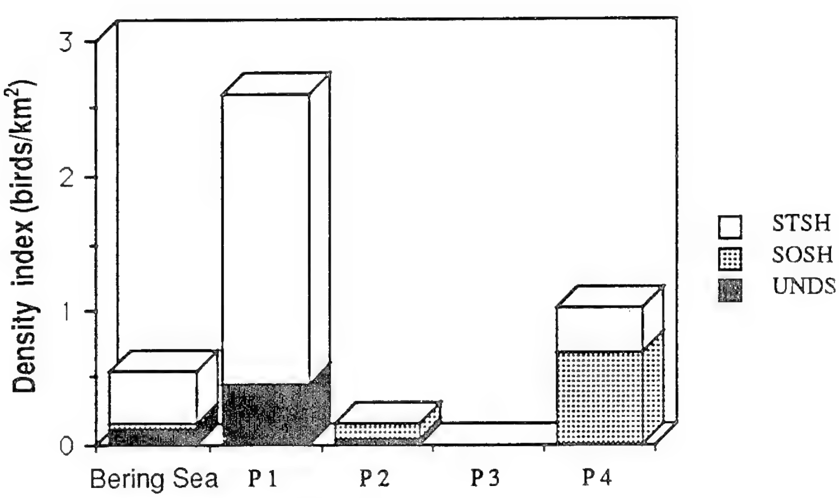

Fig. 15. Shearwaters by polygon in the Bering Sea. (See Table 2 for codes.)

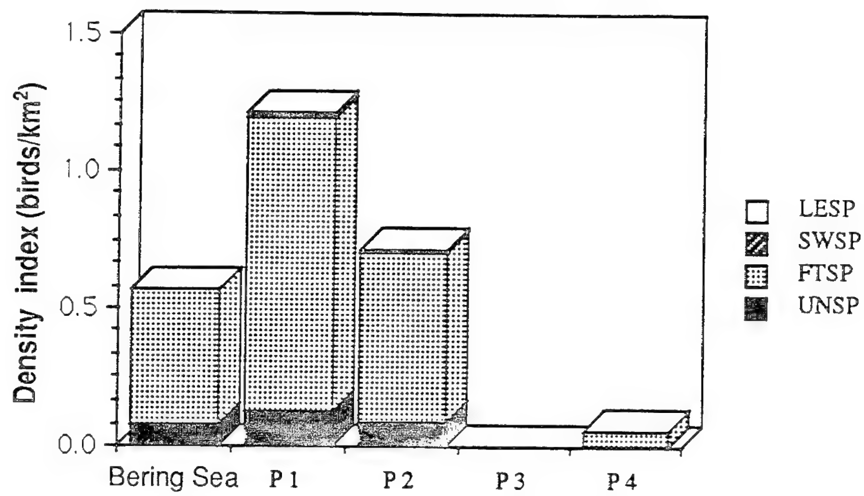

Fig. 16. Storm-petrels by polygon in the Bering Sea. (See Table 2 for codes.)

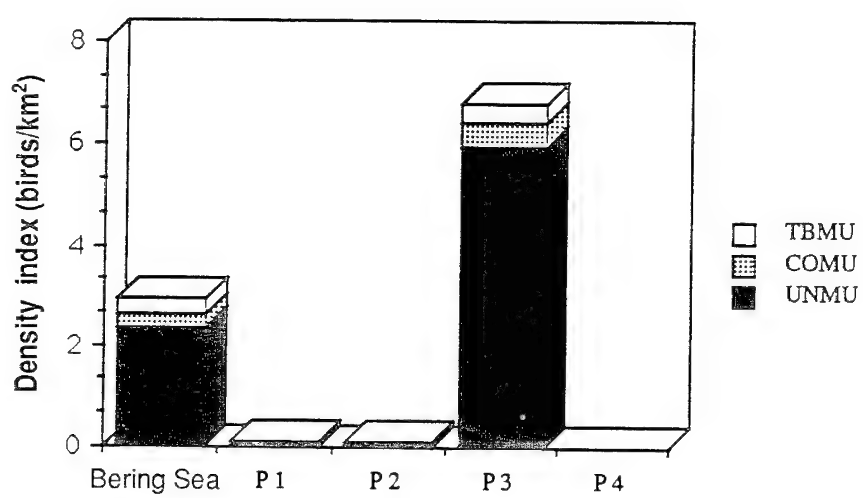

Fig. 17. Murres by polygon in the Bering Sea. (See Table 2 for codes.)

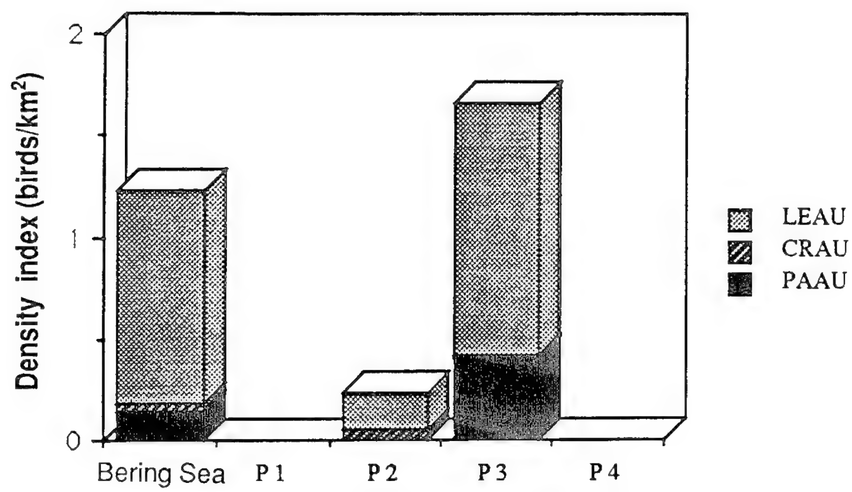

Fig. 18. Auklets by polygon in the Bering Sea. (See Table 2 for codes.)

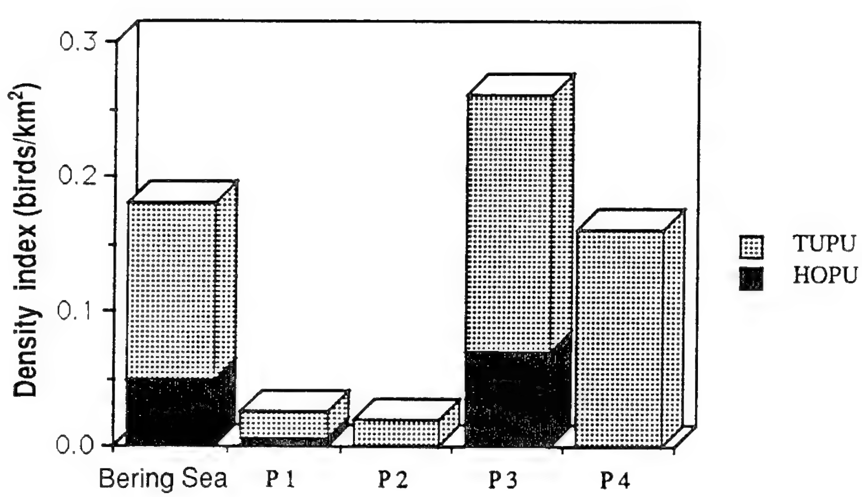

Fig. 19. Puffins by polygon in the Bering Sea. (See Table 2 for codes.)

Sooty shearwater. A total of 21 individuals were identified throughout the cruise. All but one of these were over water depths greater than 950 m east of 169°55.0'E (polygons 1 and 3). The remaining bird was seen at 54°31'N, 171°15'W. The largest sighting was a group of six birds over Shirshov Ridge.

Short-tailed shearwater. Regular in small numbers throughout deeper waters of the Bering Sea. The only birds found over the Continental Shelf were several individuals and an aggregation of 500 very near the shelfbreak in the Zhemchug Canyon area northeast of the Pribilof Islands. The only other large group was 81 short-tails at 54°01.6'N, 175°36.7'E.

Fork-tailed storm-petrel. The distribution of this species was the same as that of short-tailed shearwaters although fork-tailed storm-petrels were of much more regular and frequent occurrence (Table 2). The largest aggregations observed were birds around the ship during station counts at 54°31.8'N, 178°55.8'W (46 birds) and 54°12.3'N, 177°6.2'E (28 birds), both locations being at depths greater than 3,500 m and the latter having a surface water temperature of 8.9°C. The high frequency of occurrence for this species, as with northern fulmars, may be at least partially related to their tendency to be attracted to ships.

Leach's storm-petrel. Four individuals were observed, the northernmost at 57°26.1'N, 173°41.6'W over a water depth of 140 m and surface temperature of 7.3°C. The remaining birds were over depths greater than 3,500 m and one was over surface water of 6.7°C.

Swinhoe's storm-petrel. A single bird watched for over 5 min at a distance of about 200 m at 54° 00.0'N x 175°47.2'E over a water depth of 3,900 m and surface temperature of 60°C.

Pelagic cormorant. Two birds, one in breeding plumage, at 54°04'N, 179°05'E.

Harlequin duck. An adult female at 58°00'N, 170°00'E.

Ruddy turnstone. A single bird circled the ship at 58°34'N, 170°28'E.

Phalarope. Three sightings; three birds at 54°04'N, 179°05'E; one bird at 62°41'N, 174°42'W; and three birds at 54°46'N, 169°42'E.

Pomarine jaeger. Widely distributed through all habitats. Of the 51 birds recorded, 84% were light phase. One adult at 58°00'N, 170°00'E was completely black even in the wings. No differences in the distribution patterns of the two color phases was evident.

Parasitic jaeger. Six light-phase birds were observed, all east of 179°W.

Long-tailed jaeger. Five light-phase birds were recorded, all over the Shirshov Ridge.

Herring gull. Seven single birds and a group of eight were found, all north of 63°N. These birds were within 55 nmi of land and the large group was 18 nmi from the Soviet mainland.

Slaty-backed gull. One bird was observed at 64°00'N, 173°28'W, 18 nmi from the Soviet mainland.

Glaucous-winged gull. Seven birds were found, all south of 58°01'N.

Black-legged kittiwake. Frequent and abundant throughout the Bering Sea. Highest densities occur when individuals and small groups accumulate around the ship during stops at oceanographic sampling stations. In most cases, high numbers were the result of the accumulation of individuals and small groups of birds around the ship when it was stopped for oceanographic sampling. Counts of 50 or more individuals occurred only four times during the cruise; three of these cases (175, 215, and 264 birds) were over the Zhemchug

Canyon area of polygon 2. In the fourth case 96 birds were west of St. Lawrence Island in polygon 3.

Red-legged kittiwake. Eighteen birds, including one group of seven, were found between 170°W and 175°W about 125 nmi north of the Aleutian Islands over depths of 3,000-3,500 m. Two other individuals were recorded at 58°N, 175'W and 58°N, 170'E over depths of 2,900 m and 1,800 m, respectively.

Sabine's gull. A single bird observed over the Shirshov Ridge in polygon 4 on July 19.

Terns. Two unidentified terns were seen at 63°58'N, 172°29'W, flying towards the Soviet mainland.

Common murre and thick-billed murre. Murres were very abundant over the northern Bering Sea shelf (polygon 3) and absent from the Shirshov Ridge area (polygon 4). Single transect density indices ranged from 0 birds/km^2 to over 48 birds/km^2. Highest densities were recorded 19-35 nmi west of St. Lawrence (Table 10). Beyond that distance, indices held relatively constant out to a distance of 100 nmi. Thick-billed murres made up 55% of all murres identified to species during this study.

Pigeon guillemot. Twelve birds gathered around the stopped ship 43 nmi southwest of St. Mathew Island, a group of six was observed around the stopped ship 18 nmi south of Cape Chukhotskiy, and two birds were observed flying together during a transect 37 nmi west of St. Lawrence Island.

Ancient murrelet. Two birds were seen together on the water 160 nmi north of Attu Island.

Parakeet auklet. Found only over the Continental Shelf within 70 nmi of St. Mathew and St. Lawrence Islands. The greatest numbers were located in the strait between St. Lawrence Island and the Soviet mainland. Most sightings were of single birds and the largest was a group of five.

Least auklet. Abundant over the continental shelf in all areas visited within 90 nmi of St. Mathew and St. Lawrence Islands. Two small groups, one of five and one of six birds, were observed flying north over the continental slope (1,000 m) about 157 nmi NW of the Pribilof Islands. Flock sizes ranged from 1 to 27 birds and averaged 4.3 for 67 sightings.

Crested auklet. The fact that only nine birds of this common species were found during this study indicates that their major foraging areas were outside of our cruise pattern. One bird, apparently feeding, and two other birds were observed in the Zhemchug Canyon area 135 nmi northwest of the Pribilof Islands. Four birds were seen about 30 nmi west of St. Mathew Island and two single birds were found in the strait between St. Lawrence Island and the Russian mainland.

Tufted puffin. These birds were frequently recorded in small numbers over both deep and shallow waters and were found in all polygon areas. This was the sixth most frequently sighted species during the cruise. Sightings were of one or two birds, but rarely three.

Horned Puffin. Most sightings were made over continental shelf waters in the areas of St. Mathew and St. Lawrence Islands. None were recorded in polygons 1 and 4 and only a few were found in polygon 1. All but three of the 14 sightings were of single birds.

Discussion

Density indices for comparing past and future marine bird and mammal populations in the Bering Sea were calculated from data obtained during this cruise and are presented in Tables 3-9. These observations are in general agreement in terms of both density and distribution

Table 10. *Distribution of murres in relation to distance from land in the Bering Sea.*

Location	Time (h)	Density index mean ± 2 SE	Major behavior	Number transects
10-20 nmi N to NW St. Lawrence Island	1400-1720	1.9 ± 1.3	Fly to land	14
19-34 nmi SW to NW St. Lawrence Island	1430-1850	13.8 ± 5.9	Fly from land	18
18-51 nmi W to NW St. Lawrence Island	1820-2200	5.0 ± 2.2	Feed and fly from land	16
30-40 nmi SW to NW St. Mathew Island	1400-1850	8.7 ± 2.9	Feeding	19
60-85 nmi SW to W St. Lawrence Island	0820-1115	6.9 ± 2.3	Fly to land	12
85-105 nmi WSW St. Lawrence Island	1710-1820	3.6 ± 2.0	Feed and fly from land	7

patterns with other work that has been conducted in the Bering Sea (e.g., Shuntov 1972; Gould et al. 1984). Although the sample sizes are small and the data are best interpreted only at relative broad levels, there is no indication that current marine bird and mammal populations in the Bering Sea are significantly different than they have been in the recorded past, with the obvious exception of much reduced whale populations. From the standpoint of data collected on this cruise, the Bering Sea ecosystem appears to be in good condition.

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Chemistry of Polluting Substances

BIOGEOCHEMICAL CYCLE OF BENZO(A)PYRENE

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The Bering Sea is located at the periphery of the Pacific Ocean between the coast of the Asian continent on the west, the Alaska Peninsula on the east, and the chain of Aleutian Islands on the south. Because of its geographical position, this highly productive region of the World Ocean is a considerable distance away from the main potential sources of pollution of the marine environment (i.e., industry, transportation, and areas with developed economic activity). Some of the pollutants generated by these sources can remain in the marine environment for many years, exerting a hazardous influence on the biotic component of the ocean. They include carcinogenic polycyclic aromatic hydrocarbons (PAH) the majority of which are of anthropogenic origin. It was shown earlier (Shabad et al. 1976; Shabad and Il'nitskiy 1979; Tsyban et al. 1985c) that compounds of this series, in particular, benzo(a)pyrene (BP), are present in the ecosystems of various areas of the oceans and seas (North Atlantic, Baltic, and Caspian Seas, etc.), circulating and accumulating in the waters, bottom sediments, and biota, and the concentration of PAH depends mainly on the proximity of the pollution sources. In this connection, the study of elements of the biogeochemical cycles of BP in the ecosystems of the marginal Bering Sea, which has not been exposed to any appreciable contamination thus far, is of particular interest.

Comprehensive studies of the elements of the biogeochemical cycles of BP in the Bering Sea, conducted in July 1984 during the cruise of the RV *Akademik Korolev*, were a continuation of the research begun in 1981.

The study of BP distribution was carried out at stations of four polygons, located in different geographic regions of the sea, differing in hydrological conditions and biological water cycle. The location of the polygons made it possible to extend the studies to deep-sea regions (down to 4,000 m) as well as to zones of the continental slope and northern shoal waters of the continental shelf.

The studies were done on:

- seawater from the surface microlayer (SML)--a zone of active inflow and transformation of pollutants--to deep levels, including bottom ones,
- bottom sediments, and
- plankton communities in the 45- to 10-m layer.

Also assessed was the possible natural level of elimination of BP from the marine environment in the course of its microbial transformation by bacterioneuston and bacterioplankton communities.

For purposes of BP analysis, depending on the level, 1-L samples were taken with 200-L

or 1-L bottles, and also with a metal screen collecting the SML. The sampling of plankton and bottom sediments was done with a Juday net and an Okean-50 bottom sampler.

Extraction of BP from seawater, air-dried samples of biota, and bottom sediments was done with benzene, with subsequent separation of the components by thin-layer chromatography.

In accordance with standard procedure (Fedoseeva and Khesina 1968), quantitative determination of BP in all the samples analyzed was done in n-octane solutions by use of combined additions and an internal standard using quasiline fluorescence spectra in the 404-401 nm region.

In setting up model experiments with the aim of estimating the biodegradation potential of the microflora from the conversion of BP, the water containing the bacterial population of the levels studied was poured into special flasks of 0.5-L capacity, and sterile seawater was used as the control. The amount of BP introduced into the flasks in acetone solution provided for an initial concentration of 1 μg/L in the medium. To create nearly natural experimental conditions, the sets of flasks were placed in a bath with circulating outside water. The magnitude of microbial conversion of BP in the course of 10 days in in situ models was estimated from the difference between the residual concentrations in the control and in the experiment, and expressed in percentage of the initial BP mass.

In the deep waters of the south polygon, located in the Aleutian Basin (down to 4,000 m), at the western end of the Aleutian Islands, the BP content varied in the range 1.3-36.8 ng/L, including in the SML, 10-14 ng/L. Although water masses of 10 m or more were characterized by minimum BP levels (2-5 ng/L), in the southern portion of the polygon, closest to Blizhniy Island (U.S.A), an increase of BP content to 34-36 ng/L at the 45-m level was observed. This duplicated the situation noted at the same stations in 1981, when the 25-m and 45-m layers showed particularly high BP concentrations, 250 and 400 ng/L, respectively. In addition, the BP level in waters of the polygon was 23-48 ng/L in the SML at that time, with a maximum in the southern portion, and decreased with depth, on average, to 7 (1-100 m) and 2 (500-2,000 m) ng/L. The average values of BP concentrations in waters of individual levels of the stations, examined in 1981 and 1984, are listed in Table 1.

The east polygon, located on the eastern continental slope, has a dissected bottom configuration with a depth drop from 120 m in the northeast to 2,500 m in the central and southwestern portions. In comparison with the other areas studied, the BP content of the waters of this polygon at different levels was, on average, the lowest and fairly uniform (0- to 25-m layer, including the SML); this differed appreciably from the period of the preceding studies, when the SML of this area showed the maximum accumulation of BP, in the 90-170 ng/L range. Nevertheless, in the southeastern, relatively shallow portion of the polygon, at depths of 45 m, the zones of higher BP concentrations (up to 46.4 ng/L), also observed in 1981 (Tsbyan et al 1985b), were preserved.

The geographical position of the north polygon largely determined its special place among the other studied areas of the sea. Its water area located in the shelf zone of St. Lawrence Island (U.S.A.) was characterized by shallow depth (55-70 m), a low temperature of the water masses, and the presence of potential sources of PAH as a result of the high level of economic activity on the island.

On the approach to the shoal of the north polygon (section B-C) at the 45-m level, one of the three absolute maxima of BP (300 ng/L) was recorded. However, in other water samples taken at this station from the 0- to 100-m layer, this maximum did not exceed 15 ng/L. The

Table 1. *Average content of BP (in ng/L) in waters of the Bering Sea in 1981 and 1984.*

Period of study	Polygon	Surface micro-layer	Levels				
			1m	10m	25m	45m	100m
1984	South	---	6.3 ± 2.6	3.61 ± 1.43	4.46 ± 1.59	15.5 ± 6.5	6.3 ± 0.79
	East	5.01 ± 0.91	4.26 ± 1.65	4.0 ± 0.82	3.61 ± 0.98	10.77 ± 1.47	8.56 ± 5.36
	North	7.58 ± 1.79	10.73 ± 7.38	6.23 ± 1.9	7.78 ± 2.53	5.63 ± 1.47	---
	West	21.95 ± 11.02	5.64 ± 1.1	5.0 ± 1.46	7.93 ± 2.65	11.8 ± 5.78	6.6 ± 1.09
1981	South	31.3 ± 8.32	8.6 ± 2.8	---	2.75 ± 0.75	8.2 ± 2.1	10.3 ± 3.7
	East	100.8 ± 27.2	6.8 ± 1.53	---	33.0 ± 2.3	8.5 ± 4.9	10.8 ± 5.6
	North	92.25 ± 13.2	14.0 ± 7.3	---	14.6 ± 5.73	10.75 ± 0.38	7.8 ± 3.01
	West	81.0 ± 11.7	26.3 ± 8.94	---	22.5 ± 6.5	29.0 ± 8.9	---

highest concentrations were also noted in the northeastern portion of the north polygon, closest to St. Lawrence Island, in the local zones in the SML (up to 1,000 ng/L) and at the 25-m level (up to 960 ng/L). In the remaining areas of the north polygon, BP was present in considerably smaller amounts, in the 1-17 ng/L range, and its distribution was fairly uniform throughout the water mass from the surface down to bottom levels. Although in 1981 the accumulation of BP in the SML of the entire water area of the north polygon was considerably higher (16-132 ng/L), its maximum quantities were also observed in the water area adjacent to St. Lawrence Island (up to 1,200 ng/L). It should be noted that similar concentrations of BP, which exceed its solubility in water, can be caused by the accumulation of PAH in the composition of oil slicks or concentrated PAH discharges.

The west polygon (central station 58°N, 170°W), located at the same latitude as the eastern ones, is characterized by considerable depths (down to 2,800 m) and a dissected bottom configuration--the slopes of the Shirshov Ridge.

In this area, as compared to the other polygons, the greatest variability was noted in the BP content of the SML (2-43.4 mg/L for an average of 22 ± 11 ng/L), with a relatively uniform distribution of this content in the 1- to 100-m layer (Table 1), no greater than 15.5 ng/L. The waters of the 45-m level at one of the stations of the southwestern portion of the polygon were an exception (28.6 ng/L). The total level of the BP content in waters of the western polygon, as compared to the data of previous studies, was considerably lower both in the upper 100-m layer and, in particular, in the SML, which in 1981 contained from 55 to 180 ng/L. During both observation periods, waters with a BP content no greater than 3 ng/L were distributed only in the deep-sea levels (500-2,000 m) on both sides of the submerged ridge.

In order to establish the basic trends in the character of the distribution, as well as the levels of accumulation of BP in waters of the Bering Sea that took place in July 1984, an estimate was made of the frequency of individual intervals of BP concentrations in the total number of analyzed samples separately for the SML and the 0.01- to 100-m layer.

The value of 112 ng/L was taken as the upper limit of the analyzed values on the scale of the frequency of BP concentrations.

The distribution of BP in waters of the SML was characterized by a significant frequency of minimum concentrations, falling within the 0- to 16-ng/L range in 82% of the cases (Fig. 1), and in one-third of these samples, its concentrations did not exceed 5 ng/L.

Except for some isolated cases, there was no appreciable accumulation of BP in the bottom-1- to 100-m layer; in 87% of the samples, its concentrations were minimal--up to 16 ng/L. At large depths, the BP level decreased, reaching zero values.

Studies of samples of bottom sediments from areas of the sea with depths from 40 to 3,900 m revealed different concentrations of BP and confirmed the existence of PAH accumulation processes in this component of the Bering Sea ecosystem in all the polygons studied (frontispiece).

The BP content of the upper 10-cm layer of bottom sediments in 1984 ranged from 0.08 to 2.16 μg/kg, with an average of 0.25$\pm$0.04 μg/kg, and correspond to a level of .1 μg/kg, which was several (2-3) orders of magnitude below the levels observed in the impact areas of the Baltic Sea (Tsyban et al. 1985a). The highest concentrations of BP (on the average, 0.33 μg/kg), including its maximum amounts (2.16 μg/kg), were observed in the sediment of the eastern polygon. The sediment of the north shelf and of the deep-sea region of the west polygon contained smaller amounts of PAH (on the average, 0.27 and 0.16 μg/kg, respectively) (Fig. 2).

Altogether, in comparison with the preceding period of studies, the BP content of the bottom sediments of the polygons was somewhat lower, and on the average, amounted to only 0.37 of the level noted in 1981, and in isolated cases, less than 0.05. However, at some stations of the north and also east polygons, the trends in the accumulation of BP in the bottom sediments remained unchanged, and the observed

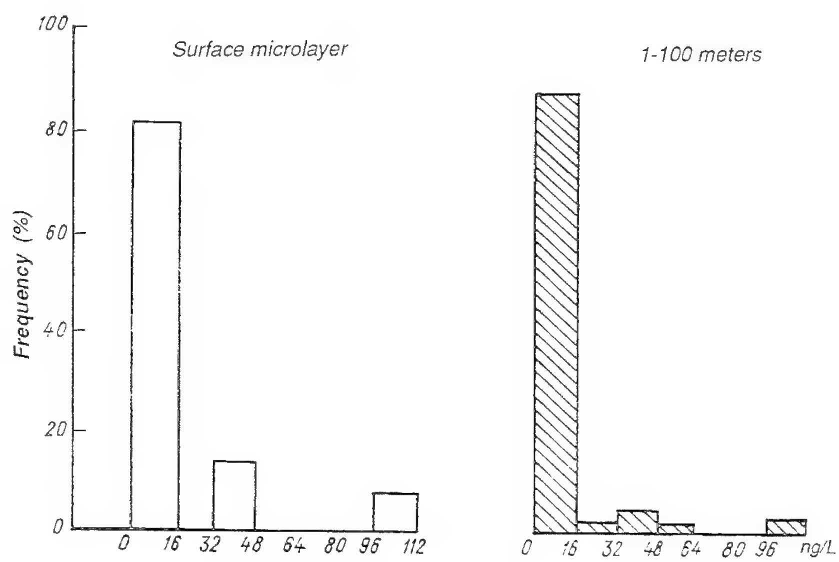

Fig. 1. Histogram of distribution of benzo(a)pyrene concentrations in waters of the Bering Sea.

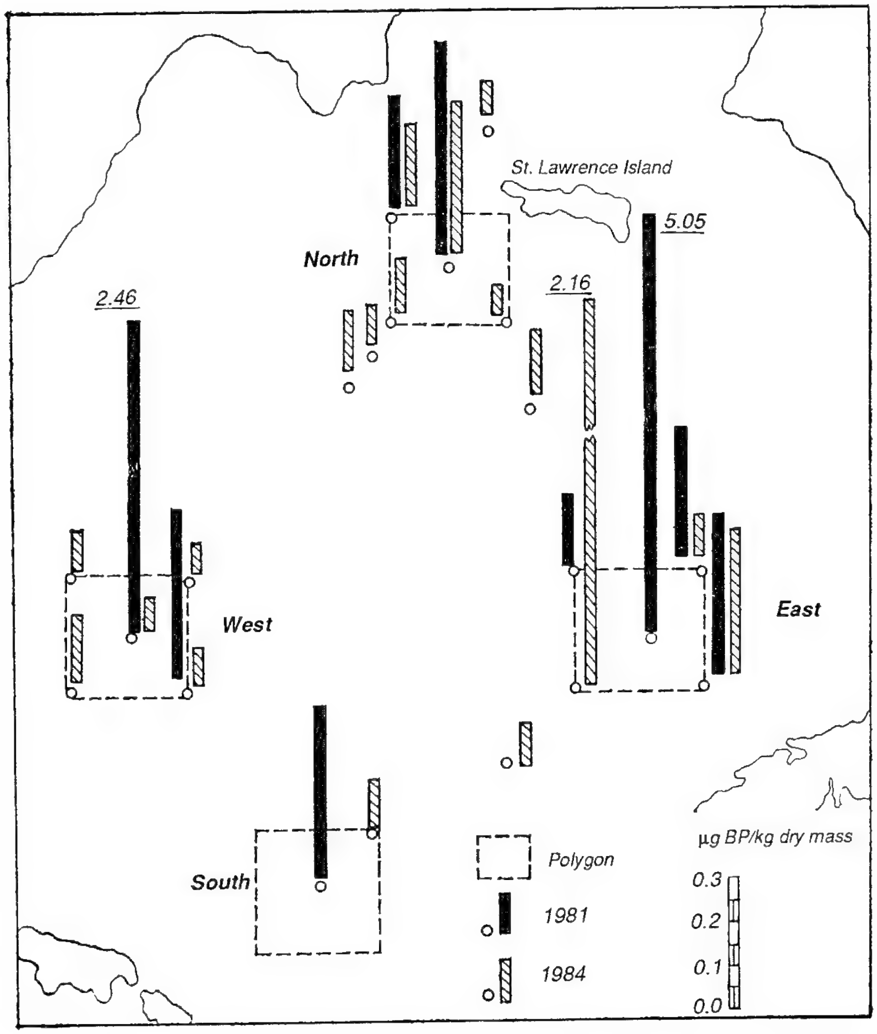

Fig. 2. Content of benzo(a)pyrene in the seabottom of the Bering Sea in 1981 and 1984.

differences in the 1984 and 1981 concentrations corresponded to values of 0.72-0.94. It should be emphasized that during both periods of studies, the region of highest BP content in the marine sediment was observed in the southwestern portion of the east polygon.

The extensive distribution of BP in the marine environment had an appreciable effect on the biotic component, particularly as expressed in the accumulation of this toxic compound in certain biota (primarily, the plankton), and also in the distribution in seawater of a specific microflora which has an appreciable biodegradation potential in relation to BP.

The presence of BP was noted in all the samples of planktonic organisms, over a fairly narrow range of concentrations, from 1.2 to

17.5 μg/kg of dry mass (Table 2). The most uniform content of BP (3.0-3.6 μg/kg) was established in the plankton of the water area of the east polygon, and its greatest accumulation was observed in the north polygon at a station east of St. Lawrence Island. The average value of BP concentrations discovered in planktonic organisms was 6.78 ± 1.4 μg/kg, which is slightly below the observed maximum of 17.5 μg/kg.

Table 2. *Content of benzo(a)pyrene in plankton of the Bering Sea in 1984.*

Polygon	Station no.	BP in water[a]	BP in plankton[b]	Coefficient[c]
South	3	0.002	5.79	10^3
	2	0.005	14.00	10^3
East	5	0.0003	3.66	10^4
	6	0.003	3.38	10^3
	7	0.002	3.02	10^3
	9	0.008	11.07	10^3
Transect E-N	10	0.001	1.22	10^3
North	12	0.014	8.66	10^3
	14	0.006	17.50	10^3
	16	0.009	7.80	10^3
	17	0.003	1.60	10^2
Transect N-W	18	0.005	1.13	10^2
West	21	0.013	13.80	10^3
	22	0.006	1.60	10^2

[a]Content of BP at the water level 25 m, μg/L
[b]Content of BP in plankton, μg/kg of dry mass.
[c]Coefficient of accumulation of BP by plankton (BP in plankton/BP in water).

Altogether, the BP content of the plankton of the polygons studied corresponded to a level of .1 μg/kg, which is an order of magnitude below the minimum concentrations observed in the plankton of the Baltic Sea (Tsbyan et al. 1985a). It should be noted that during the preceding study period, the presence of BP in the planktonic organisms of the Bering Sea was considerably (by a factor of 10-100) higher (up to 2,900 μg/kg) and amounted to an average of 129.8 μg/kg. This may be due to the phenomenon, observed in 1981, of higher BP content in all the elements of the Bering Sea ecosystem. However, the preservation of a hazardous trend toward an intensive bioaccumulation of BP is indicated by slight differences (on the average, no greater than one order of magnitude) in the coefficients of its accumulation by the plankton from the seawater environment in the periods of 1981 and 1984 (Table 3).

The distribution of BP-transforming microflora in the water masses of the Bering Sea exhibited a patchy character, and its density was mainly 10^1-10^2 cells/mL. Modeling of processes of microbial decomposition in in situ experiments lasting 10 days showed the potential possibility of transformation of 7% to 66% of the BP introduced in an initial concentration of 1 ng/L, which corresponded to its maximum level found in seawater.

In all the experiments, the greatest biodegradation potential was exhibited by the bacterioneuston communities populating the SML. With increasing depth, in particular, greater than 25 m, the level of microbial transformation of BP dropped appreciably, reaching zero values (Fig. 3) in some cases (bottom waters of the northern polygon). At the same time, the data obtained indicate the possibility of its transformation by the microbial population of deep-sea levels (eastern polygon, 500 m).

Of all the areas studied, the maximum biodegradation potential was exhibited by the

Table 3. *Coefficients of accumulation of BP by plankton in the Bering Sea in 1981 and 1984.*

$$K = \frac{\text{BP in plankton}}{\text{Bp in water}}$$

Polygon	Period of observations 1981	1984
South	10^4	10^3
	10^5	10^3
	10^4	
East	10^2	10^4
	10^4	10^3
	10^4	10^3
	10^4	10^3
North		10^3
	10^4	10^3
		10^3
West	10^5	10^3
	10^4	10^2
Average values in all polygons	10^4	10^3

microflora of waters of the north polygon in the entire 0- to 25-m layer of waters, and particularly in the SML (59% of the BP introduced was transformed). An analogous estimate of this area, located near St. Lawrence Island, was given in 1981. The absolute maximum of activity (66.3%) was recorded in experiments with the SML microflora of the eastern polygon. The extent of microbial transformation of BP in waters of the southern and western polygons was at a lower and uniform level, in the 19%-20% range.

Studies of these processes, conducted in different years (1981 and 1984), indicate a certain stability of the biodegradation potential of the microflora of individual areas of the sea, expressed in similar values of BP transformation in different periods of experiments (Table 4). Altogether, the activity level of the Bering Sea microflora with respect to the transformation of BP was somewhat higher in 1984 and corresponded to the values noted in similar experiments in waters of the Baltic Sea (Tsyban et al. 1985a).

Studies of the elements of biogeochemical cycles of PAH, illustrated by the example of BP, conducted in the Bering Sea, indicate the presence of this toxic and carcinogenic compound in many components of its ecosystem.

The BP concentrations discovered in seawater in 1984 did not exceed 16 ng/L in most cases (some of them were located in the region of the natural background) and were fairly uniform in the entire 0- to 100-m layer. At large depths, its content dropped to minimum values, close to zero.

The distribution of high BP concentrations had a nonuniform local character, and their maxima (up to 1 ng/L) were observed in the water area of the north polygon, close to St. Lawrence Island. In comparison with the situation observed during previous studies in 1981, the total BP content of the seawater (particularly in the SML) was appreciably lower (by 1 to 2 orders of magnitude), and its vertical distribution was characterized by great uniformity and the absence of distinct concentration peaks at individual levels.

The accumulation of BP in the other components of the ecosystem also decreased, and amounted to an average of 2.6 μg/L) for soils, and 6.78 μg/kg for plankton (i.e., to 0.3 and 0.1-0.01, respectively, of the values noted in 1981). Altogether, the data obtained indicate a certain decrease of the total PAH level in the marine environment of this region.

Nevertheless, the long-period studies performed make it possible to distinguish certain

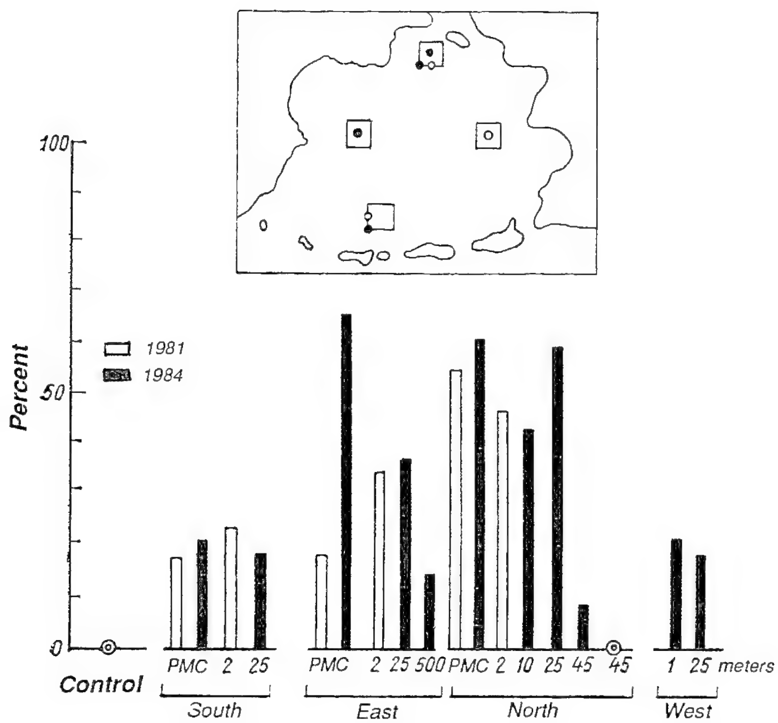

Fig. 3. Microbial transformation of BP in model experiments in situ with microflora of the waters of the Bering Sea.

trends in the processes of BP circulation that are characteristic of the Bering Sea ecosystems.

The spatial distribution of BP in the seawater is spotty: the maxima of its content, observed in local zones (in most cases, in the SML), considerably exceed the levels characteristic of open-ocean regions located at considerable distances from the continents (Shilina, n.d.).

Although no distinct relationship was found between the pollution levels of the waters and the location of PAH sources, the highest BP content of all the stations studied was in the northern region of the sea (near St. Lawrence Island), in an area exposed to the influence of economic activity, and also in waters of the eastern polygon, this being consistent with observations made in 1977 (Izrael 1983).

The maximum accumulation of BP took place in the bottom sediments of the east polygon. Although the BP concentrations observed in the Bering Sea groups were 1-2 orders of magnitude below the levels existing in groups of polluted areas of the World Ocean, the observed facts of BP deposition in the bottom sediments indicate a general distribution of PAH in the Bering Sea environment. This makes it possible, in view of the minimum stability of certain compounds of this series, to regard the bottom sediments of the sea (particularly in its shallow areas) as a depot of chemical toxicants which constitute a potential source of secondary pollution of the marine environment.

The phenomenon of bioaccumulation of BP by planktonic organisms is characteristic of as well as deep areas and was manifested in the

Table 4. *Comparable value of potential capacity capability of microflora of the waters of the Bering Sea to transform BP in experiments in situ.*

Polygon	Level	Transformation of BP in % of initial concentration of entering BP[a] 1984	1981	Relative magnitude of transformation (1984/1981)
North	PMC	59	54	1.1
	2-25	49.5[b]	45[c]	1.1
East	PMC	66.3	18	3.7
	2-25	38.6[d]	35[c]	1.1
South	PMC	19.3	17	1.1
	2-25	18.6[d]	22[c]	0.8

[a]transformation of BP in the control 0% shallow
[b]average value at the 10-m (41%) and 25-m (58%) levels
[c]data at the 2-m level
[d]data at the 25-m level

bioaccumulation of BP in the 1-3,000 μg/kg range (Tsyban et al. 1985b).

Although as a whole, the BP content of the plankton differed appreciably during the 1981 and 1984 periods, partition coefficient of this compound in planktonic organisms remained at a fairly high level, 10^3-10^4. The highest rate of this process was characteristic of the productive areas of the northern and western polygons.

The bacterial population of Bering Sea waters adapted to the conditions of presence of PAH in the marine environment and, relative to BP, had an appreciable biodegradation potential which reached a level of 0.6 μg/L in 10 days under in situ experimental conditions. The most distinct activity, which remained at the same level during the 1981 and 1984 periods, was exhibited by the bacterioneuston and bacterioplankton of the northern and eastern areas of the sea. The studies indicate an important role of the microflora in the processes of elimination of organic pollutants in this subarctic region of the World Ocean. Thus, the comprehensive studies of the elements of biogeochemical cycles of PAH, conducted in the Bering Sea, have shown a wide distribution of BP in this basin. The general character of the distribution and concentration of BP in the components of the Bering Sea ecosystem, and the existence of a microflora adapted to these conditions, indicate that PAH are constant and characteristic factors in the majority of the areas of the Bering Sea.

The active circulation of BP in the marine ecosystem and its presence in the composition of the constant hydrochemical background for a number of years indicate the existence of intensive flows of PAH in this area. In view of the remoteness of this area of the World Ocean from the main industrial regions and the limited extent of penetration of human-made PAH, a basic role in the formation of the BP level existing in the marine environment is

probably played by long-range atmospheric transport of pollutants and by certain natural sources. Included in the latter are PAH flows of volcanogenic and petroleum origin (natural discharges of petroleum hydrocarbons from the sea floor).

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CHLORINATED HYDROCARBONS

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Chlorinated hydrocarbons, primarily pesticide preparations (CH) and polychlorobiphenyls (PCB), make up one of the few classes of organic compounds whose inflow is totally connected with human economic activity. Long-term use of these stable chlorinated organic compounds in many countries of the world has resulted in their practically universal distribution and accumulation in marine ecosystems. According to recent estimates (Tanabe 1982), the World Ocean contains approximately 230,000 tons of PCB. The average PCB concentration in ocean waters is as follows: in the Atlantic Ocean, 1.0 ng/L, in the northern Pacific Ocean, 0.5 ng/L, in the southern Pacific Ocean, 0.12 ng/L, in the Indian Ocean, 0.14 ng/L, and in the Antarctic seas, 0.05 ng/L (Tanabe 1982, 1984, 1985; Pearson 1983; Subramanian et al. 1983). The main sources of penetration of chlorinated hydrocarbons into the marine environment are the surface runoff of the continent (mainly via rivers) and atmospheric transport (dry precipitation or settling).

Highly toxic and stable, chlorinated hydrocarbons, both chlorinated organic pesticides and PCB, can accumulate in aquatic organisms and be transmitted along the food chain.

In this connection, the study of the content and distribution of chlorinated hydrocarbons in biotic and abiotic components of marine ecosystems is important and necessary.

This paper presents the results of a study of the distribution of chlorinated hydrocarbons in the ecosystem of the Bering Sea—a region of the World Ocean located at a considerable distance from populated and industrial areas of the Asian and American continents. In this region, penetration of PCB with the surface runoff is practically nonexistent, and the great variety of the ichthyofauna makes it possible to assess the characteristics of the bioaccumulation of these substances by different species of fish.

Materials and Methods

In order to study the content and distribution of chlorinated hydrocarbons in different components of the Bering Sea ecosystem during the second period of the Soviet-American expedition in the Bering Sea in July 1984, samples of seawater, bottom sediments, benthic organisms, plankton, and fish were collected, then analyzed on board the RV *Akademik Korolev*. The sampling sites are indicated in the frontispiece.

The seawater samples, which were first filtered through a membrane filter with a pore diameter of about 45 m, were passed through a column packed with KhAD-2 resin. The sorbed organic substance was eluted off the column with ethanol, then the eluate was treated with a 1 N KOH solution. The water-alcohol solution obtained was extracted twice with n-hexane. The extract was concentrated to a volume of approximately 2 mL, then purified with concentrated sulfuric acid, and additionally purified by passing through a column with partially deactivated florisil. The fractionation was carried out with n-hexane (PCB, HCCH, DDE) and a 1:3 ether-hexane mixture (DDT, DDD, chlordanes, chloroterpenes).

Samples of the surface microlayer of water were taken with metallic sieves, subjected to liquid-liquid extraction with n-hexane, and analyzed like samples of seawater.

The biological specimens and samples of bottom sediments were homogenized, extracted twice with a hexane-acetone mixture, and subjected to the above-mentioned procedure of concentration and purification.

The gas-chromatographic analysis was done without a splitter and with use of an electron capture detector. The analysis conditions were as follows: quartz capillary column, 25 m x 0.22 mm, stationary phase of BP-1; film thickness, 0.6 μm; carrier gas, nitrogen (1.5 kg/cm^2). The temperature was programmed from 40°C (0.7 min) to 190°C at a rate of 50°C/min; after holding the temperature at 190°C for 3 minutes, to 250°C at a rate of 2°C/min; and after holding the temperature at 250°C for 10 minutes to 300°C at a rate of 5°C/min.

The peaks were identified by comparing the holding times on the chromatogram of the analyzed sample to the holding times of standard solutions of chlorinated organic pesticides, polychlorobiphenyls, and chlordanes (Fig. 1).

Discussion of Results

Data on the content of chlorinated hydrocarbons in different components of the Bering Sea ecosystem are shown in Tables 1-4.

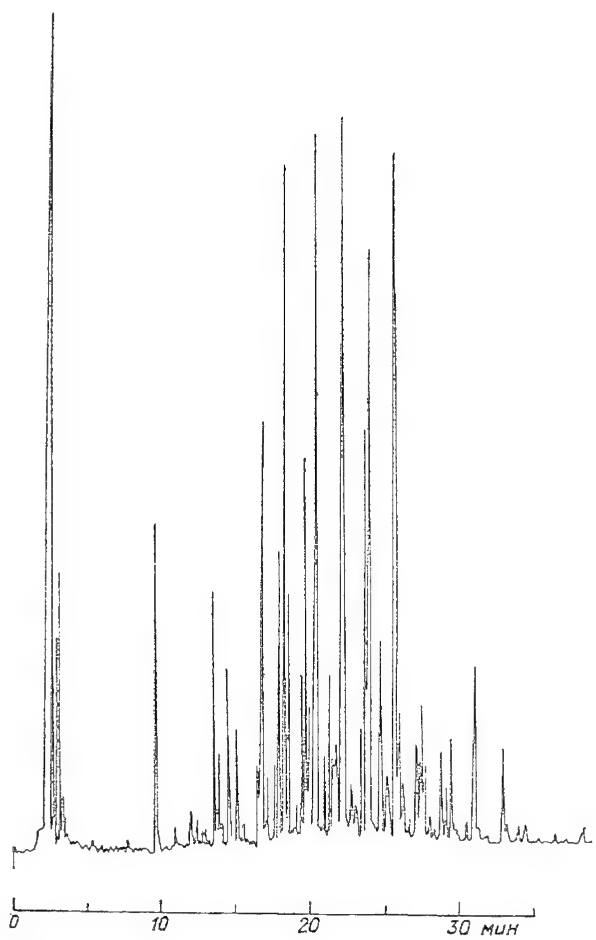

Fig. 1. Chromatogram of standard solution of polychlorinated biphenyls.

Table 1. *Content of chlorinated hydrocarbons in fish.*

Station no.	Subject	Organ	Concentrations (ng/g of dry wt.) DDT	PCB
1	Pollock-5	liver	4.2	20.3
		muscles	0.7	3.2
		spleen	1.2	6.9
		gonads	0.4	1.9
		brain	0.8	4.5
		gill arch	1.3	8.3
	Pollock-6	liver	4.2	22.8
		muscles	0.5	2.9
		blood	0.2	1.1
		spleen	1.4	7.3
		gonads	0.5	2.7
		brain	0.6	3.1
		gill arch	0.2	8.5
	Pollock-7	liver	2.8	13.3
		muscles	0.6	2.9
		spleen	0.2	1.2
		brain	0.4	2.2
		gill arch	0.4	2.2
2	Pollock-8	muscles	0.9	4.0
		spleen	1.0	4.4
		gonads	0.5	2.4
		brain	0.5	2.3
	Pollock-9	liver	3.2	15.7
		muscles	0.6	3.5
		spleen	0.9	5.0
	Pollock-10	liver	3.5	16.9
		muscles	0.3	2.8
		spleen	0.5	6.3
		gonads	0.2	3.5
		brain	0.2	4.1
	Pollock-11	spleen	0.6	3.7
		brain	0.5	2.7
3	Pollock-17	liver	2.2	12.1
		muscles	0.9	5.7
		spleen	0.8	4.2
		gonads	0.7	3.6
		brain	0.7	4.2
	Pollock-18	spleen	1.2	7.0
		gonads	0.6	3.4
		brain	0.8	4.5
	Pollock-19	liver	3.4	15.1
		muscles	1.2	5.9
		spleen	0.6	2.6
		gonads	1.2	5.5
	Pollock-20	liver	1.3	7.9
		muscles	0.5	3.0
		spleen	0.3	1.8
	Pollock-21	gonads	0.4	2.3
		brain	0.9	5.1
5	Pollock-22	liver	0.3	2.7
		muscles	0.2	1.3
		gonads	0.3	2.6
		brain	0.2	3.8
		spleen	0.4	9.2
7	Pollock-23	liver	0.2	4.3
		muscles	0.3	1.1
		gonads	0.4	1.9
		skin	0.2	1.0
8	Pollock-24	liver	1.2	7.7
		muscles	0.3	1.5
		gonads	0.5	2.5
		spleen	0.4	6.7
		brain	0.2	3.8

Table 1. *Continued.*

Station no.	Subject	Organ	Concentrations (ng/g of dry wt.) DDT	PCB
	Pollock-25	liver	4.7	4.4
		muscles	0.3	2.2
		gonads	0.3	2.9
		brain	0.2	3.7
	Pollock-26	liver	2.3	2.7
		muscles	0.5	1.3
		gonads	0.4	3.1
		spleen	0.3	4.3
	Pollock-27	muscles	0.3	2.7
	Pollock-28	liver	0.8	4.5
		muscles	0.2	1.0
		spleen	0.6	3.3
		brain	0.7	3.1
		gonads	0.2	1.1
	Pollock-29	liver	3.5	7.3
		muscles	0.3	1.0
		spleen	1.0	6.1
		gonads	0.4	2.9
	Pollock-30	livertrace	2.7	
		musclestractrace		
9	Pollock-31	muscles0.3	4.1	
20	Pollock-34	muscles0.42.5		
		gonads0.84.3		
		brain0.84.7		
	Pollock-36	muscles	0.5	2.4
	Pollock-38	muscles	0.2	1.2
	Pollock-39	liver	5.2	22.2
		muscles	0.5	1.7
	Pollock-40	muscles	0.2	1.3
		spleen	1.0	9.0

Station no.	Subject	Organ	Concentrations (ng/g of dry wt.) DDT	PCB
21	Pollock-42	muscles	0.4	2.5
	Pollock-43	muscles	0.4	2.6
	Pollock-44	muscles	0.4	2.3
	Pollock-45	muscles	0.4	1.8
	Pollock-46	muscles	0.4	1.3
		gonads	0.4	4.3
	Pollock-47	muscles	0.2	1.2
	Pollock-48	muscles	0.2	1.7
	Pollock-49	muscles	0.2	1.7
		gonads	0.3	4.1
	Pollock-50	muscles	0.2	1.9
		spleen	0.5	7.2
	Pollock-51	muscles	0.3	1.4
		gonads	0.4	2.6
		spleen	0.4	4.5
22	Pollock-55	muscles	0.5	2.6
	Pollock-56	liver	7.2	31.1
		muscles	0.5	2.7
		gonads	0.9	5.7
		spleen	1.1	9.2
	Pollock-57	gonads	0.3	2.2
		spleen	0.8	7.1
	Pollock-58	liver	5.5	21.6
		muscles	0.4	2.2
		gonads	0.5	3.1
		spleen	0.2	1.5

Table 1. *Continued.*

Station no.	Subject	Organ	Concentrations (ng/g of dry wt.) DDT	PCB
	Pollock-59	liver	3.4	17.2
		muscles	0.3	1.3
		gonads	0.8	5.5
		spleen	0.9	6.8
	Pollock-60	liver	2.5	14.2
		muscles	0.3	1.2
		gonads	0.4	3.3
		spleen	0.4	4.7
	Pollock-61	liver	6.5	33.4
		muscles	0.3	2.1
		gonads	0.5	4.2
		spleen	1.7	10.2
	Pollock-62	liver	3.7	15.8
		muscles	0.3	1.2
		gonads	0.6	3.2
		gill arch	0.4	2.7
23	Pollock-63	liver	4.7	25.6
		muscles	0.2	1.7
		gonads	0.4	2.8
		spleen	1.2	9.8
	Pollock-64	liver	5.5	28.1
		muscles	0.3	1.2
		gonads	0.5	2.1
		spleen	1.1	9.3
	Pollock-65	liver	8.0	37.6
		muscles	0.5	1.4
		gonads	0.5	2.6
		spleen	1.4	10.5
	Pollock-66	liver	5.6	25.3
		muscles	0.4	1.7
		gonads	0.4	2.4
		spleen	0.9	10.8
	Pollock-67	liver	2.3	7.7
		muscles	0.3	1.2
		gonads	0.4	3.9
		spleen	0.4	3.5
	Pollock-68	liver	5.5	28.8
		muscles	0.6	1.4
		gonads	0.6	4.7
		spleen	0.7	10.6
	Pollock-69	liver	6.5	29.7
		muscles	0.4	1.9
		gonads	0.7	6.1
		spleen	0.9	10.7
25	Pollock-70	liver	3.5	18.8
		muscles	0.3	2.1
		gonads	0.8	5.3
		spleen	0.9	6.8
	Pollock-71	liver	7.7	41.2
		muscles	0.4	3.1
		gonads	0.3	2.7
		spleen	0.9	12.7
	Pollock-72	muscles	0.5	2.5
		spleen	1.2	11.1
	Pollock-73	liver	7.6	40.3
		muscles	0.2	2.1
		gonads	0.3	2.5
		spleen	0.7	12.2
	Pollock-74	liver	7.8	37.2
		muscles	0.3	1.7
		gonads	0.4	2.9
		spleen	1.2	13.3
	Pollock-75	liver	5.5	28.2
		muscles	0.3	1.9
		gonads	0.4	3.0
		spleen	1.4	10.9
	Pollock-76	liver	9.5	44.4
		muscles	0.4	1.9
		gonads	0.7	4.1
		spleen	1.5	10.3

Table 1. *Continued.*

Station no.	Subject	Organ	Concentrations (ng/g of dry wt.) DDT	PCB
	Pollock-77	liver	7.5	37.1
		muscles	0.5	2.7
		gonads	0.9	5.3
		spleen	1.9	10.4
	Pollock-78	liver	3.4	18.2
		muscles	0.4	1.9
		gonads	0.4	2.6
		spleen	1.5	9.2
	Pollock-79	liver	6.6	32.9
		muscles	0.2	2.1
		gonads	0.3	2.9
		spleen	0.9	13.7
26	Pollock-80	liver	3.2	14.7
		muscles	0.3	2.7
		gonads	0.4	3.0
		spleen	1.1	7.1
	Pollock-81	liver	5.7	28.1
		muscles	0.6	2.5
		gonads	0.6	3.7
	Pollock-82	liver	5.4	29.2
		muscles	0.4	2.3
		gonads	0.4	4.1
		spleen	1.3	12.6
	Pollock-83	liver	7.9	41.4
		muscles	0.6	3.3
		gonads	0.8	4.4
		spleen	1.2	13.5
14	Bullcalf-1	liver	9.2	39.8
		muscles	1.1	4.2
		gonads	1.2	5.3
		spleen	0.7	1.7
		kidneys	0.5	1.2
		brain	0.4	4.7
		gills	1.2	5.0
4	Salmon-1	gonads	0.3	2.4
		liver	2.5	13.2
		spleen	0.3	4.1
		muscles	0.2	4.4

The results obtained showed that the concentration of PCB in water (surface microlayer (SML) and the integrated surface layer) ranged from 0.5 to 0.8 ng/L. It should be noted that these results are substantially higher than the values noted by Japanese investigators in 1981 and approach the values obtained for heavily polluted coastal areas of the Baltic Sea (Chernyak and Mikhaleva 1985).

A characteristic feature of the composition of PCB in the water samples was the predominance of components with three chlorine atoms in the molecule, comprising approximately 70% of the total PCB content: components with two and four chlorine atoms comprised 22% of the total, with pentachlorobiphenyls and hexachlorobiphenyls accounting for only 8% of the PCB mixture, and highly chlorinated biphenyls with 7-9 chlorine atoms were not detected in the sample at all. Samples from the surface microlayer had a fundamentally different composition. The chromatograms recorded heptachlorobiphenyls, and the fraction of tetra-, penta-, and hexa- derivatives increased (to 25%, 12%, and 5% respectively), with trichlorobiphenyls predominating as before (42%).

The indicated facts can be explained by the variation of the solubility of PCB in seawater

(from hundreds of ng/L for low-molecular components to fractions of ng/L for highly chlorinated compounds). The high content of nonpolar organic compounds in SML apparently leads to a narrowing of the solubility limits of the PCB components and a relative leveling of the contents of the different fractions.

Table 2. *Content of chlorinated hydrocarbons in benthic organisms.*

Station no.	Subject	Concentrations (ng/g of dry wt.) DDT	PCB
5	Crustacea	12	61
	Asteroidea	25	53
	Ascidiae	34	72
	Spongia	5	21
	Pisces, Macruridae	18	58
6	Pisces, Mictophydae	13	33
9	Asteroidea	21	71
10	Asteroidea	10	28
11	Bivalvia	8	53
	Pagurus sp.	4	7
	Gastropoda	22	72
	Ophiuroidea, *Ophiura sarsi*	11	81
13	Hydroidea	5	38
	Ophiuroidea, *Ophiura sarsi*	3	59
	Crustacea	11	60
	Gorgonocephalus carwi	49	102
	Ascidiae	21	52
	Pisces, Perciformes	13	72
	Spogia	16	28
	Echinoidea	40	93
18	Bivalvia	21	44
	Ophiuroidea	18	71
23	Polychaeta	14	67
24	Asteroidea	3	73
	Ophiuroidea	12	62
	Polychaeta	19	66
	Spongia	2	40

Table 3. *Content of chlorinated hydrocarbons in benthic deposits.*

Sample no.	Station no.	Concentrations (ng/g of dry wt.) DDT	PCB
1	1	1.3	0.7
2	2	1.6	2.4
3	3	0.5	0.5
4	10	0.4	2.7
5	12	0.9	1.5
6	13	1.7	3.4
7	14	3.4	9.5
8	15	2.0	1.8
9	16	0.8	9.2
10	17	1.4	3.3
11	18	1.2	2.8
12	19	0.7	1.3
13	20	0.4	3.7
14	21	0.3	1.9
15	22	1.2	3.5
16	23	1.5	3.1
17	24	1.5	5.7
18	25	0.2	2.5

Table 4. *Content of chlorinated hydrocarbons in plankton.*

Sample no.	Station no.	Concentrations (ng/g of dry wt.) DDT	PCB
1	5	1.2	2.9
2	9	1.5	3.5
3	16	2.3	5.4
4	17	1.1	3.3
5	18	1.1	2.7
6	22	1.8	4.1

Analysis of walleye pollock (*Theragra chalcogramma*) samples showed that the maximum accumulation of chlorinated hydrocarbons takes place in the liver. The content of polychlorobiphenyls varies in the range 2.7-44.4 ng/g of fresh weight (average value, 9.5 ng/g) and the content of chlorinated organic pesticides of the DDT group—0.2-8.0 ng/g of fresh weight (average, 2.5 ng/g); the 4.4'-DDD component predominates in the samples: this usually indicates the presence of metabolic processes taking place directly in the fish organism. Other organs with a lower fat content accumulate correspondingly lower amounts of chlorinated hydrocarbons: muscle tissue, 0.2-1.2 ng/g of DDT and 1.2-5.9 ng/g of PCB; gonads, 0.2-1.2 ng/g of DDT and 1.1-6.1 ng/g of PCB; spleen, 0.2-1.9 ng/g of DDT and 1.2-13.7 ng/g of PCB; brain, 0.2-0.9 ng/g of DDT and 2.5-5.1 ng/g of PCB; gills, 0.2-1.4 ng/g of DDT and 2.2-8.5 ng/g of PCB.

In these organs, the ratio of the components of the DDT group is more balanced, and in the composition of PCB, as in the liver sample, the predominant components present are highly chlorinated ones (i.e., pentachlorobiphenyls and hexachlorobiphenyls) because of a lower rate of their transformation in biological specimens.

The highest concentrations of pollutants in different organs of the walleye pollack were noted in zones of comparatively heavy navigation, and the lowest concentrations were observed in the subpolar area of the Bering Sea (Table 1).

The accumulation of hydrocarbons of the DDT and PCB groups is manifested even more in the case of benthic organisms. The content of hydrocarbons of the DDT group varied in the range 3-49 ng/g of fresh weight; that of PCB, 21-102 ng/g; in the PCB fraction the content of low- and high-chlorinated biphenyls was balanced; and in the DDT fraction there was an excess of the 2.4'-4.4'-DDE components, apparently because of consumption of the already partially dehydrochlorinated mixture of DDT by benthic organisms (Table 2).

The present study did not permit us to determine the dependence of the content of chlorinated hydrocarbons in benthic organisms on their concentration in the corresponding bottom sediments, since the contamination of the upper sediment layer was found to be approximately the same in the entire sea: DDT, 0.3-3.4 ng/g of dry weight; PCB, 0.5-9.2 ng/g of dry weight (Table 3).

The study of chlorinated hydrocarbons in bottom sediments shows that the contribution of low-chlorinated biphenyls to the composition of PCB is substantially lower than in the corresponding seawater samples. This can be explained by the importance of the biosedimentation process in the formation of ocean floor sediments.

For plankton, the predominance of low-chlorinated forms of PCB was noted: this apparently can serve as proof of an appreciable contribution of the sorption mechanism in the accumulation of PCB by plankton. The predominance of 2.4-olefins among the DDT group in plankton can be explained by the characteristics of the environment of the organisms (Table 4).

Conclusions

1. Chlorinated hydrocarbons were determined in all the studied samples of the Bering Sea, both biological (benthos, plankton, fish) and abiotic (water, bottom sediments).
2. The growing use of chlorinated hydrocarbons in the world economy in the last few years has led to increased pollution of all the components of the Bering Sea ecosystem.
3. The composition of chlorinated hydrocarbons in biological specimens, which reflects the pattern of pollution of their environment, indicates a steady influx of these hydrocarbons into the Bering Sea.
4. The calculated concentrations of chlorinated hydrocarbons in the Bering Sea ecosystem

indicate the possibility of using biological specimens in monitoring this body of water.

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TRACE METAL DISTRIBUTION IN SEDIMENTS FROM THE BERING SEA

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Introduction

The Bering Sea is believed to be one of the few bodies of water that is relatively free from pollutants due to a sparse population and limited industrial development in the area. With an expansive continental shelf, the Bering Sea is also home to large quantities of finfish and shellfish important to U.S. as well as foreign fishing fleets (Hood and Kelly 1974). Increased industrial activity, especially petroleum exploration and production, is proposed for the future and thus extensive preliminary studies of the area are necessary.

During June and July of 1984, the Second Joint U.S.-U.S.S.R. Expedition to the Bering Sea was undertaken to collect biological, chemical and physical baseline data and thereby provide a comprehensive profile of the Bering Sea; to study physiological and ecological characteristics of planktonic organisms; and to assess the relative ecological health of the Bering Sea. This paper discusses the distribution of iron (Fe), copper (Cu), magnesium (Mn), zinc (Zn), lead (Pb), mercury (Hg), and cadmium (Cd) in surficial sediments collected from 12 stations sampled during the expedition. Locations of the stations are listed in Table 1 and shown on the area map (frontispiece).

Methods

Sediment Collection

Sediment collection was performed from the RV *Akademik Korolev*. All sediment samples were obtained using a gravity corer lined with 8-cm diameter cellulose-acetate-butyrate tubing. Each core was split lengthwise into two sections. One section was subsampled and the other was archived. Subsampling was done in 1-cm intervals over the top 10 cm and in 2-cm intervals below 10 cm.

Laboratory Analysis

Sediment analysis was performed on 0-1 cm intervals collected from each site. These sediment samples were digested in acid-cleaned Teflon beakers using about 0.4 g aliquots of sample with $HClO_4$-HNO_3-HCl-HF, following the process outlined in Trefry and Metz (1984). Sediment solutions and reagent blanks were analyzed for Fe, Cu, Mn, and Zn by flame atomic absorption spectrophotometry (AAS) by using a Perkin-Elmer 4000 instrument. Lead

Table 1. *Sampling station data.*

Station no.	Location	Core Length (cm)	Date sampled (m) depth	Water depth
4	56°43.8'N 178°32.0'W	60	6 July 1984	>2,000
10	59°58.8'N 174°00.4'W	152	10 July 1984	<100
11	61°30.1'N 173°40.0'W	47	11 July 1984	<100
12	63°30.1'N 173°28.7'W	138	12 July 1984	<100
15	62°58.4'N 172°29.2'W	29	14 July 1984	<100
18	62°44.1'N 174°37.1'W	76.5	17 July 1984	<100
19	62°25.4'N 175°09.7'W	42.5	18 July 1984	<100
20	58°34.0'N 170°27.7'E	173	19 July 1984	600-2,000
21	58°03.4'N 170°02.9'E	175	20 July 1984	600-2,000
22	57°23.0'N 169°31.4'E	90	21 July 1984	>2,000
24	57°28.9'N 170°42.4'E	178	23 July 1984	>2,000
25	53°46.6'N 176°19.1'E	144	25 July 1984	>2,000

and Cd were determined by flameless AAS by using a Perkin-Elmer 4000 instrument equipped with an HGA-400 heated-graphite atomizer and an AS-40 autosampler. Deuterium background correction was required for Cu, Mn, Zn, Pb, and Cd determinations. Matrix interferences were corrected by using standard additions analysis when necessary.

Mercury concentrations in each sample were determined by heating about 2 g of wet sediment in a 50-mL polyethylene centrifuge

tube with 5 mL of concentrated, redistilled HNO_3 in a 65°C water bath for about 1 h. The centrifuge tubes were then cooled for 12 h and the solutions diluted to a volume of 25 mL using distilled, deionized water. A Laboratory Data Control Mercury Monitor was used for Hg analysis. In this system the sample is treated with stannous chloride to reduce Hg to its elemental state. The elemental Hg is then carried by N_2 from the reaction vessel into a 30-cm pathlength cell where it is measured by absorption of light at 253.7 nm.

Analytical precision for determination of metal concentrations is expressed as a coefficient of variation and established from analysis of triplicate samples. Precision averaged <5% for Cd, Fe, Hg, Mn, and Pb and <1% for Cu and Zn. As a quality control check, U.S. National Bureau of Standards (NBS) estuarine sediment (SRM 1646) was analyzed. Data for trace metals analyzed in SRM 1646 agreed with certified values from NBS.

Results and Discussion

Site Description

Twelve sediment cores were collected from the Bering Sea and analyzed for trace metals. Four of the 12 cores (stations 4, 22, 24, and 25) were obtained from water depths >2,000 m (Table 1). Stations 10, 11, 12, 15, 18, and 19 are located in water depths of less than 100 m. Water depths for the remaining two stations (20 and 21) ranged from 600 to 2,000 m. The deepest core obtained was from station 25 at a water depth of 3,950 m.

Trace Metal Concentrations

Trace metal concentrations for surficial sediments varied with location and water depth. Higher concentrations were generally found for samples collected in deeper water (>2,000 meters). Sediments collected in shallower waters (<2,000 m) are believed to contain a mixture of sand and mud.

Iron and Pb concentrations in the sediment varied very little in the study area (Table 2 and Fig. 1). Iron concentrations averaged 2.87% and are only about 50% of continental crust averages (Table 2). However, they are quite comparable with the average Fe values of 2.02 to 3.13% reported by Loring (1984) for surficial sediments from Baffin Bay and the sounds leading into the Arctic Ocean. In the case of Fe, pollution is uncommon and the element often serves as a useful element to help gain a general picture of sediment composition.

Lead concentrations for Bering Sea sediments are very low everywhere at 3.6 ± 1.9 μg/g (Table 2 and Fig. 1). Iron concentrations can sometimes be used to normalize other sediment trace metal values and thereby obtain an estimate of natural and anthropogenic contributions of trace metals to the sediments. In the Bering Sea, the ratio of Pb/Fe is $1.2 \pm 0.6 \times 10^{-4}$, somewhat lower than a 2.2×10^{-4} value for continental crust (Table 3). Thus, Pb input into the Bering Sea is believed to be mostly from natural sources at present.

Manganese concentrations were generally uniform at all sites except at station 25 (Table 2 and Fig. 2). Eleven of the 12 Mn values correlate well ($r = 81$) with Fe concentrations (Fig. 3). Ratios of Mn/Fe for these 11 stations averaged about 150×10^{-4}, compared to 170×10^{-4} for continental crust. Manganese values for Arctic nearshore muds averaged 340 μg/g (Loring 1984); a Mn concentration of 14,860 μg/g reported for station 25 is believed to result from remobilization of Mn within the sediment column. The top 10 cm of the sediment column from this site had a reddish-brown color, identifying an oxidizing layer, over a grey (reducing) layer. Under these conditions, Mn is dissolved in the subsurface reducing sediments and then diffuses upward until it precipitates as an oxide phase in the top centimeters of oxidizing sediment. This high concentration of surficial Mn results from natural processes and is similar to values of 2,000 to 13,500 μg/g observed in northwest Pacific sediments (Lynn and Bonatti 1965).

Table 2. *Trace metal concentrations for surficial sediments (0-1 cm) from the Bering Sea.*

Station	Fe (%)	Cu (μg/g)	Mn (μg/g)	Zn (μg/g)	Pb (μg/g)	Hg (ng/g)	Cd (ng/g)
4	2.27	13	248	102	2.4	70	155
10	2.88	28	397	92	3.0	36	63
11	3.15	31	407	80	6.4	24	27
12	2.90	16	375	86	3.0	29	330
5	3.04	12	391	68	5.9	21	445
8	3.05	16	370	92	7.7	30	40
19	2.67	16	356	77	3.3	25	89
20	2.90	24	354	85	2.6	20	64
21	3.00	11	355	90	2.6	21	77
22	3.02	49	325	119	2.5	105	215
24	3.04	31	408	110	1.9	58	212
25	2.49	73	14,860	108	2.5	90	16
Mean (± SD)	2.87 (± 0.26)	22[a] (± 12)	362[a] (± 46)	92 (± 15)	3.6 (± 1.9)	44 (± 30)	144 (±134)
Average[b] continental crust	5.60	55	950	70	12.5	80	200

[a]excluding station 25.

[b]Taylor (1964).

More study of the area around station 25 certainly merits consideration for possible metalliferous deposits.

Concentrations of Zn and Hg in Bering Sea sediments showed some variation as a function of water depth. Sediments collected from depths <2,000 m (stations 10 to 21) had Zn levels of 84 ± 8 μg/g and Hg values of 26 ± 6 ng/g (Table 2 and Fig. 3). Sediments collected from deeper waters (stations 4, 22, 24, and 25) had significantly higher concentrations of both Zn (110 ± 7 μg/g) and Hg (84 ± 21 ng/g). These deep-water sediments were all collected

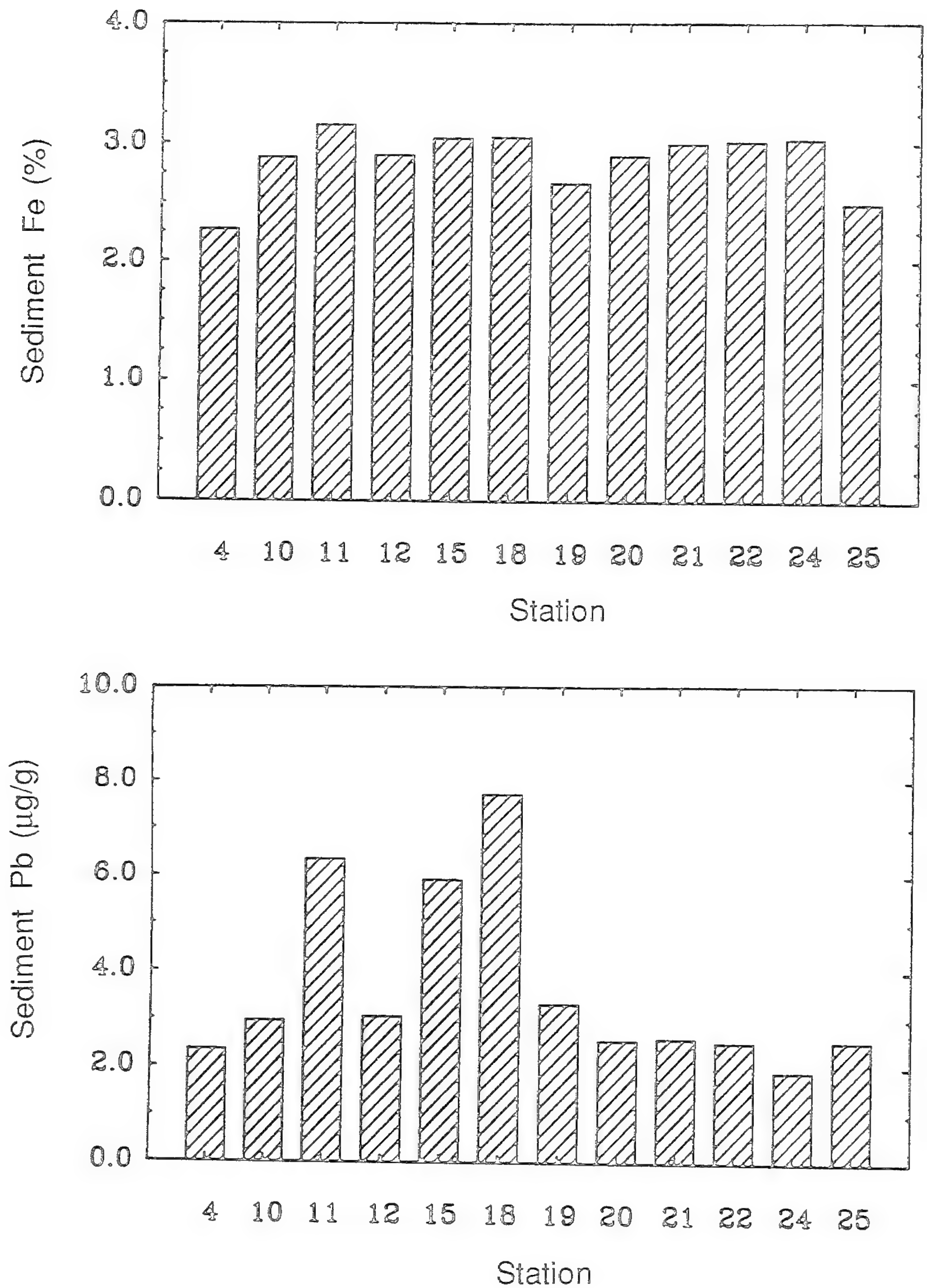


Fig. 1. Concentrations of Fe and Pb in surficial (0-1 cm) sediments from the Bering Sea.

Table 3. *Ratios of Cu, Pb, Hg, and Cd concentrations to Fe values for surficial sediments (0-1 cm) from the Bering Sea.*

Station	Cu/Fe ($\times 10^{-4}$)	Pb/Fe ($\times 10^{-4}$)	Hg/Fe ($\times 10^{-7}$)	Cd/Fe ($\times 10^{-7}$)
4	6	1.1	31	68
10	10	1.0	12	22
11	10	2.0	8	9
12	6	1.0	10	114
15	4	1.9	7	146
18	5	2.5	10	13
19	6	1.2	9	33
20	8	0.9	7	22
21	4	0.9	7	26
22	16	0.8	35	71
4	10	0.6	19	70
5	29	1.0	36	6
Mean (± SD)	10 (± 7)	1.2 (± 0.6)	16 (± 16)	50 (± 45)
Average[a] continental crust	10	2.2	14	36

[a]Taylor (1964).

from the Aleutian Basin. A linear relationship ($r = 0.88$) was found for Zn vs. Hg for all sites sampled in the Bering Sea (Fig. 4A). Elevated Zn and Hg values from the deep-water sites may be due to some natural mineral source in the southern portion of the study area or long-term scavenging of these metals from seawater. Although anthropogenic inputs cannot be totally discounted, Hg concentrations for Bering Sea sediments are only 1/260-1/140 of those for Minamata Bay and 1/40-1/20 of those reported for a contaminated African lagoon (Table 4). Average Hg concentrations for the Bering Sea were similar to Arctic nearshore muds and about 1/2 those of Baffin Bay deep-sea muds (Loring 1984; Table 4).

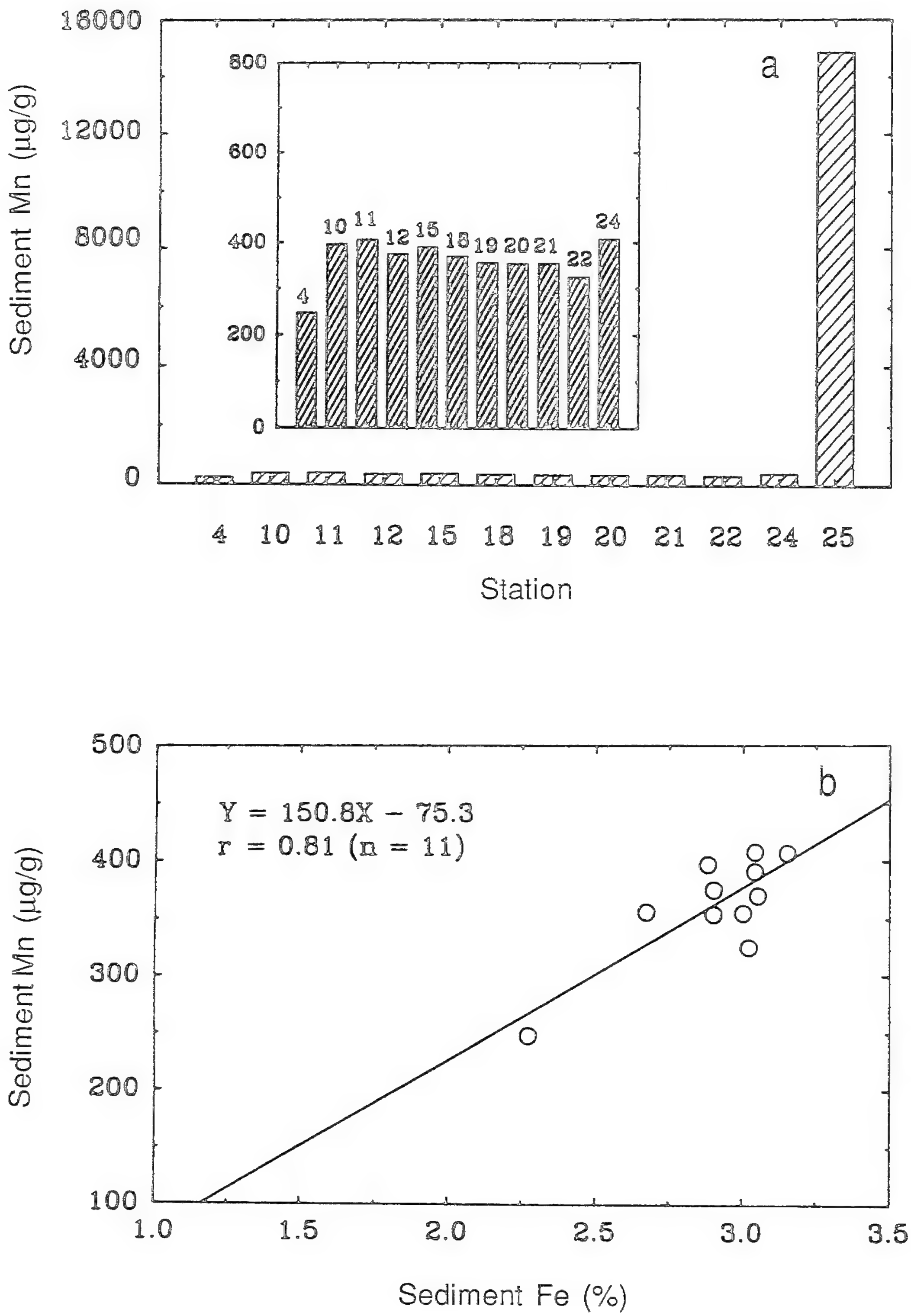


Fig. 2. (A) Concentration of Mn in surficial (0-1 cm) sediments from the Bering Sea. (B) Plot of Fe vs. Mn for Bering Sea sediments.

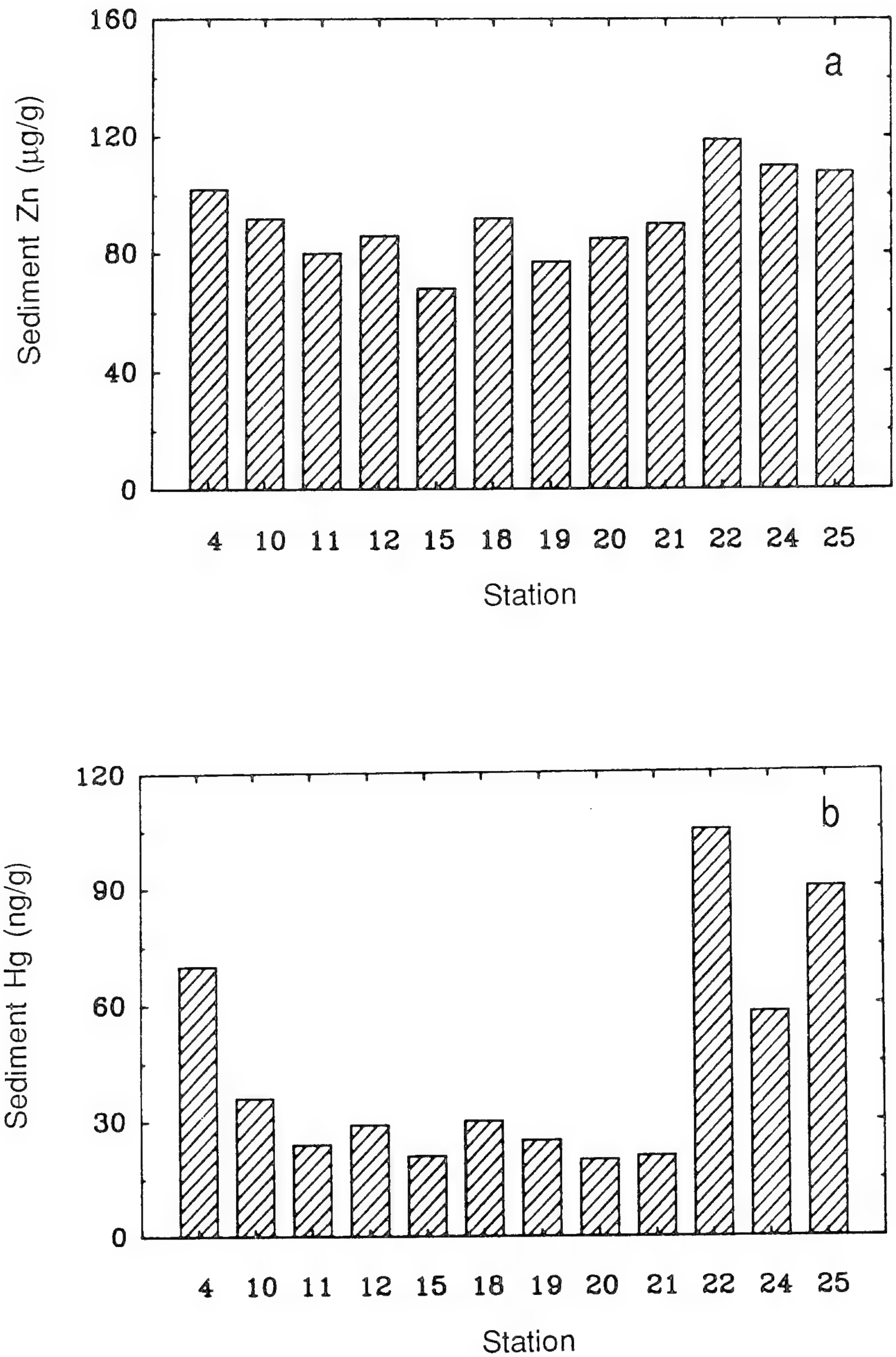
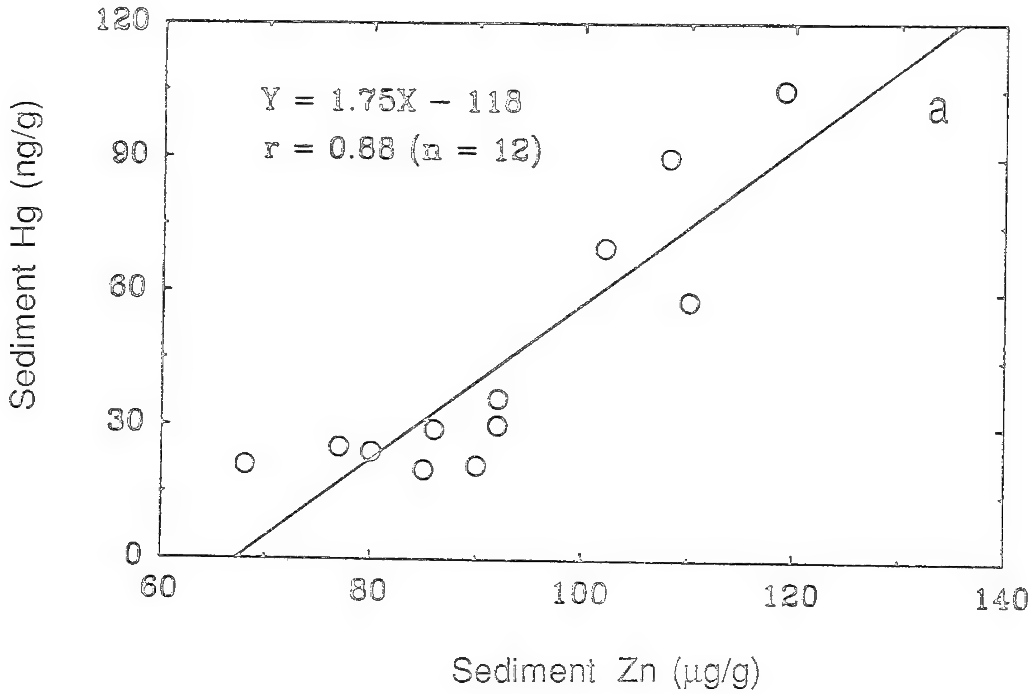


Fig. 3. Concentrations of Zn and Hg in surficial (0-1 cm) sediments from the Bering Sea.



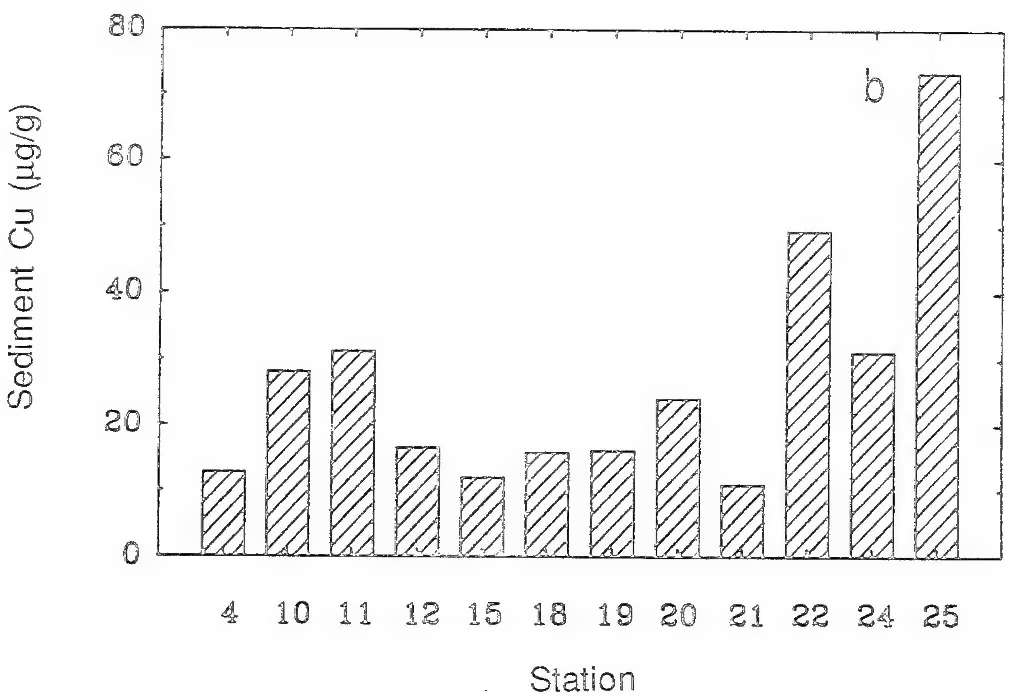


Fig. 4. (A) Plot of Zn vs. Hg for Bering Sea sediments. (B) Concentration of Cu in surficial (0-1 cm) sediments from the Bering Sea.

Table 4. *Comparison of sediment Hg concentrations in the Bering Sea with values recorded elsewhere.*

Location	Hg (ng/g)	Source
Minamata Bay	15,000	Nishimura and Kumagai (1983)
Ebrie Lagoon, West Africa	2,250	Kouadio and Trefry (1987)
Arctic nearshore muds	50	Loring (1984)
Baffin Bay deep-sea muds	90	Loring (1984)
Bering Sea	44 ± 29	

Copper concentrations show some similarity to Zn and Hg values (Table 2). The average Cu concentration of 27 ± 18 μg/g for Bering Sea sediments is similar to concentrations of 9 to 61 μg/g measured in Baffin Bay (Loring 1984). These values and their ratios to Fe show no evidence of pollutant inputs at this time (Tables 2 and 3). Station 25 had the highest Cu concentration (73 μg/g) of any of the 12 stations (Fig. 4B). This higher value is believed to result from remobilization of Cu within the sediment column.

The most interesting trace metal studied in Bering Sea sediments is Cd (Fig. 5). Generally, Cd has a distribution similar to both Zn and Hg except for stations 12, 15, and 25 (Table 2). The low Cd values observed at nine sites suggest no pollutant inputs. Stations 12 and 15 have the highest Cd concentrations (Fig. 5). Both sites are located in an area where the water depth is <65 m and primary productivity is high. The higher Cd concentrations at these sites are most likely due to a downward vertical flux of planktonic organisms and associated biogenic debris. Concentrations of Cd in Pacific Ocean plankton are reported to be 2 to 5 μg/g (dry weight), but values as high as 20 μg/g (dry weight) have been measured (Martin and Broenkow 1975). Thus, observed high Cd values for these two sites are believed to be due to a natural bioconcentration mechanism. At station 25, the Cd concentration is lower than at any of the other sites. It is possible that Cd is diffusing out of the sediments into the overlying water at station 25, resulting in a lower concentration of Cd in surficial sediment.

Conclusions

Trace-metal concentrations for the Bering Sea were generally quite uniform, with some regional variability. Two metals, Pb and Fe, had little or no variability over the entire study area. Lead concentrations were generally very low and showed little evidence of pollutant inputs. Iron concentrations are lower than average continental crust values and serve as a useful data set for normalizing other trace metal values.

Zinc and Hg concentrations varied as a function of water depth and correlated well with each other. Deeper water stations had elevated concentrations of both metals. These values are believed to be due to natural sources rather than any anthropogenic input.

The distribution of Mn in Bering Sea sediments is uniform except for station 25, where a very high concentration is believed to result from remobilization occurring within the sediment column. A correlation was found to exist between Fe and Mn for all stations except station 25. Copper distribution throughout the study area is similar to Zn and Hg except for station 25. At this site, an elevated Cu

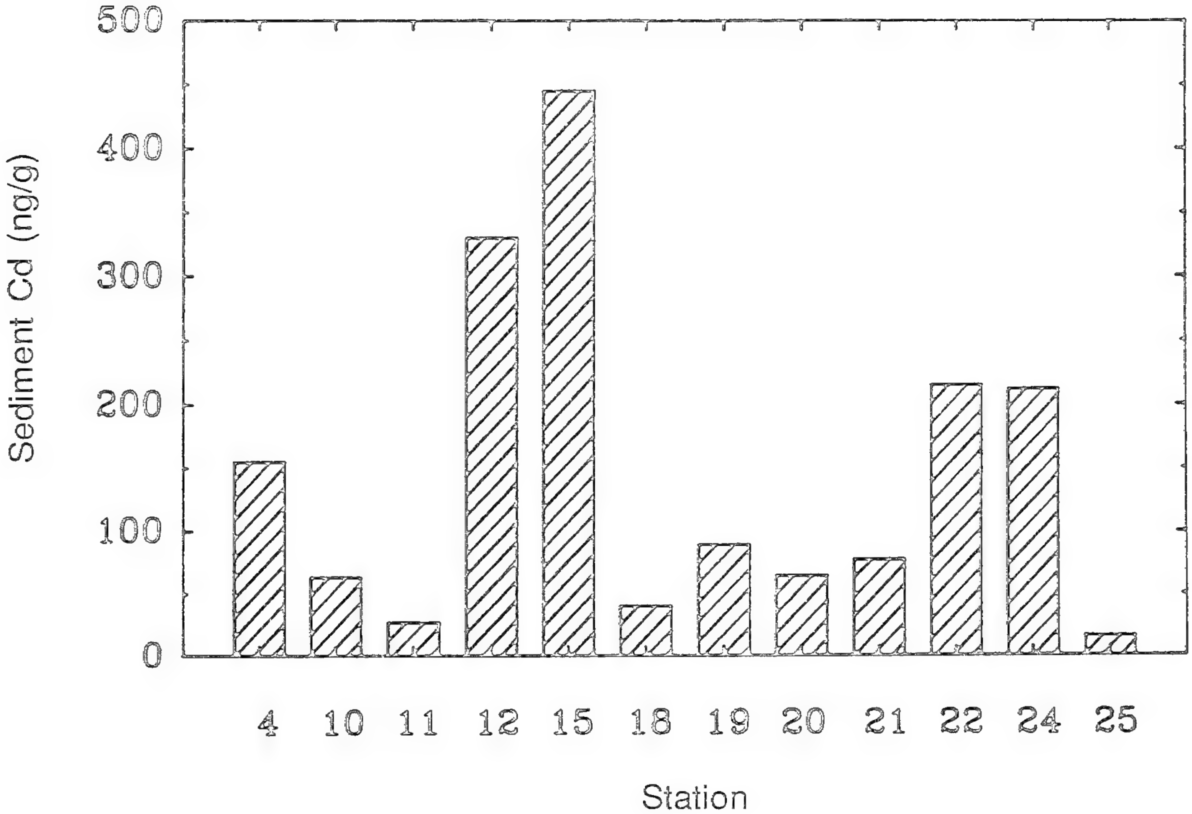


Fig. 5. Concentration of Cd in surficial (0-1 cm) sediments from the Bering Sea.

concentration in surficial sediments is believed to have resulted from remobilization. None of the 12 sites show evidence of pollutant inputs of Cu.

None of the Cd values from the 12 sites suggest pollutant inputs. Stations 12 and 15 had the highest Cd concentrations of all 12 sites sampled, the result of high primary productivity and shallow waters in this area. The primary source of Cd in this area is believed to be biogenic. The lowest Cd concentration was found at station 25, where remobilization may have removed Cd from the sediments.

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BIOGENIC SEDIMENTATION

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Functioning plankton communities form suspended organic matter whose flow from the production layer into the depths of the ocean plays an important role in the biogeochemical cycle of substances in the World Ocean. The gravity flow of suspended organic matter--biogenic sedimentation--significantly affects the redistribution of pollutants entering the marine environment and is one of the fundamental mechanisms of removal of toxicants from the photic zone. Determination of the rate of bioaccumulation and sorption of pollutants on suspended organic matter and of the rate of biosedimentation removal of these compounds from the productive layer of the ocean are necessary for estimating the assimilation capacity of marine ecosystems. Long-term observations, such as monitoring of the dynamics of removal of suspended matter from the photic layer, make it possible, on the one hand, to assess the self-purification capacity of the marine ecosystems of the pelagic zone, and on the other hand, to determine the influence of anthropogenic pollution on the ecosystems from the change in biosedimentation rate (Izrael and Tsyban 1983; Polikarpov et al. 1985).

The present paper reports the results of studies of biogenic sedimentation in the Bering, South China, and Philippine Seas conducted during the 37th cruise of the RV *Akademik Korolev*.

Methods of Investigation

To estimate the rate of removal of suspended organic matter and the magnitude of biosedimentation flow from the production layer of the ocean in the studied areas, use was made of the radiochemical method of determining the shift of the radioactive equilibrium in the uranium^{-238} - thorium^{-234} system (Polikarpov and Yegorov 1980; Polikarpov et al. 1984; Zesenko and Yegorov 1987). The uranium^{-238} concentration in seawater is relatively constant and amounts to 2.2 dis min^{-1} L^{-1} in open areas of the ocean; the shift of the equilibrium with the daughter radionuclide thorium^{-234} is caused by bioaccumulation and subsequent sedimentation of the latter with organic particles. Thus, having determined the vertical distribution profiles of thorium^{-234}, one can calculate the rate of removal of organic matter from different layers of the ocean.

The thorium^{-234} concentration in seawater is low; therefore, in order to increase the accuracy of the determinations, this isotope was first chemically separated from large-volume water samples. Water from different levels, selected on the basis of a preliminary sounding of the vertical distribution of temperature and salinity, was sampled with 200-L water-sampling bottles; the volume of one sample was 100 L. The water samples were placed in transparent plastic containers and acidified with concentrated hydrochloric acid to pH 4; 10 mL of acidified ferric chloride solution was then added (in the amount of 1 g of Fe^{3+} per sample) and mixed, and 500 g of ammonium chloride was added. Thorium^{-234} was separated from the water by coprecipitating with iron hydroxide and gradually adding a 25% aqueous solution of ammonia to

pH 9 with constant stirring. After 12-24 hours, the precipitate was decanted and transferred to a paper filter, which was then dried. The precipitate on the filter was dissolved with 100-150 mL of 8 M HCl. The solution obtained was passed through an ion-exchange column with KU-2 resin in H form at a rate of 0.5 mL/min. The volume of the resin was 30 cm^3. The eluent used was 8 M HCl. The elution was carried out until the disappearance of the yellow color of the eluate (i.e., until the ferric chloride was completely washed away). The ion-exchange resin was transferred to porcelain cups, dried, and ignited in a muffle furnace at 450-500°C. The remaining ash was ground up to a homogeneous state and transferred to aluminum supports. The β activity of the prepared samples was measured with an SBT-13 counter in lead shielding with a PSO2-08 scaler. The relative error of the radiometric measurements did not exceed 20%. The counting efficiency was 13.5%-16.2%. The radiochemical yield of thorium^{-234} during coprecipitation with iron hydroxide, determined from the radiochemical yield of thorium^{-232}, was assumed to be 80% (Polikarpov et al. 1984; Zesenko and Yegorov 1987). The purity of the isolated thorium^{-234} preparation was checked on the decay curve (the half-life of thorium^{-234}, $T_{1/2}$, is 24 h).

The calculation of absolute concentrations of thorium^{-234} in seawater was made by using the formula

$$A = \frac{r}{f \circ d \circ V} \tag{1}$$

where A is the thorium^{-234} concentration at the given level (dis min^{-1} L^{-1}),

f is the efficiency of β-activity measurement with the SBT-13 instrument employed,

d is the radiochemical yield of thorium^{-234} during the coprecipitation: V is the volume of the seawater sample (1), and

r is the radioactivity of the sample (ppm).

We then calculated the rate of biosedimentation of suspended organic matter from the water layer studied:

$$P_B = \frac{\lambda Th^{(1-R)}}{k \cdot R} \tag{2}$$

where P_B is the rate of removal of suspended organic matter of the given level (mg C m^{-3} day^{-1}),

R is the ratio of the concentrations of thorium^{-234} (A) to the equilibrium concentration of uranium^{-238} (2.2 dis min^{-1} L^{-1}) in seawater,

λTh is the radioactive decay constant of thorium^{-234} per day, and

k is the coefficient of accumulation of thorium^{-234} in suspended organic matter.

The coefficient of accumulation of thorium^{-234} was determined as the ratio of the concentrations of this isotope in suspended organic matter in the area studied and in seawater under conditions of radiochemical equilibrium with uranium^{-238}. Several studies (Tsunogai et al. 1980; Zesenko and Yegorov 1987) have shown that in the northern Pacific Ocean, the concentration of thorium^{-234} in suspended organic matter is relatively stable, does not manifest any appreciable seasonal or spatial variations, and amounts to an average of 1.7 dis min^{-1} g^{-1} of C. Based on these data, we used k = 0.77 g of C/L for the calculations of the biosedimentation rate.

Results of the Studies

Removal of ^{234}Th from the photic layer of seas and oceans takes place as a result of biosedimentation processes (Hyde 1961; Tsunogai and Minagava 1976; Zesenko and Yegorov 1987). It was shown earlier that the coefficients of accumulation of thorium in living planktonic organisms and dead suspended organic matter are the same (Cherry and Shannon 1974), and thus, the rate of removal of thorium^{-234} from a specific layer of water is determined by the total amount of suspended organic matter in this layer and by the rate at which particles settle out of it. In areas of high biological productivity, the displacement of radioactive equilibrium ^{234}Th/^{238}U and correspondingly, the rate of biogenic sedimentation turn out to be considerably higher than in oligotrophic waters of the

World Ocean. Thus, the Bering Sea is one of the most productive seas in the World Ocean (Izrael and Tsyban 1983; Korsak 1987).

The highest sedimentation rates of suspended organic matter during the period of the studies in the Bering Sea were observed in areas characterized by high values of primary production, at several stations of the north polygon (stations 14 and 17) and west polygon (station 21). The general trend of the vertical distribution of the concentration ratio $^{234}Th/^{238}U$ in the Bering Sea was an increase in R with depth (starting at approximately 70 m), and appreciable shifts of the radiochemical equilibrium in the upper mixed layer (Fig. 1, Table 1). Within the confines of the euphotic zone, the variations of the biosedimentation rate were fairly appreciable: from layer to layer, the rate of removal of organic matter changed by a factor of 2-3. At great depths (below 70-100 m), changes in the value of this parameter with depth amounted to 5%-30%.

In the Pacific Ocean, along the Kuroshio Current (stations 27, 33), the vertical distribution of ^{234}Th concentrations in water in the entire layer studied (0-200 m) was more uniform than in the Bering Sea. The value of R varied in the range 0.27-0.55, gradually increasing with depth. However, in the Kuroshio section, no such sharp differences in thorium^{-234} concentrations were noted in the layer above the thermocline and at large depths, as was the case in the Bering Sea (Fig. 2). The biosedimentation rate in this area was substantially lower than in the Bering Sea; the maximum value of this parameter during the studies here amounted to 10.20 mg C m^{-3} day^{-1} (Table 1).

In the southern area of the studies, in the South China and Philippine Seas, the nature of the vertical distribution of thorium^{-234} was similar to the distribution of this isotope in the Bering Sea. The $^{234}Th/^{238}U$ activity ratio varied in the range 0.13-0.84 (Fig. 2). The biosedimentation rate was high down to depths of 70-100 m, and dropped sharply in the 100 to 200-m layer. The rate of removal of suspended organic matter in the euphotic zone varied in the range 9.02-25.24 in the South China Sea and 4.82-15.15 mg C m^{-3} day^{-1} in the Philippine Sea,

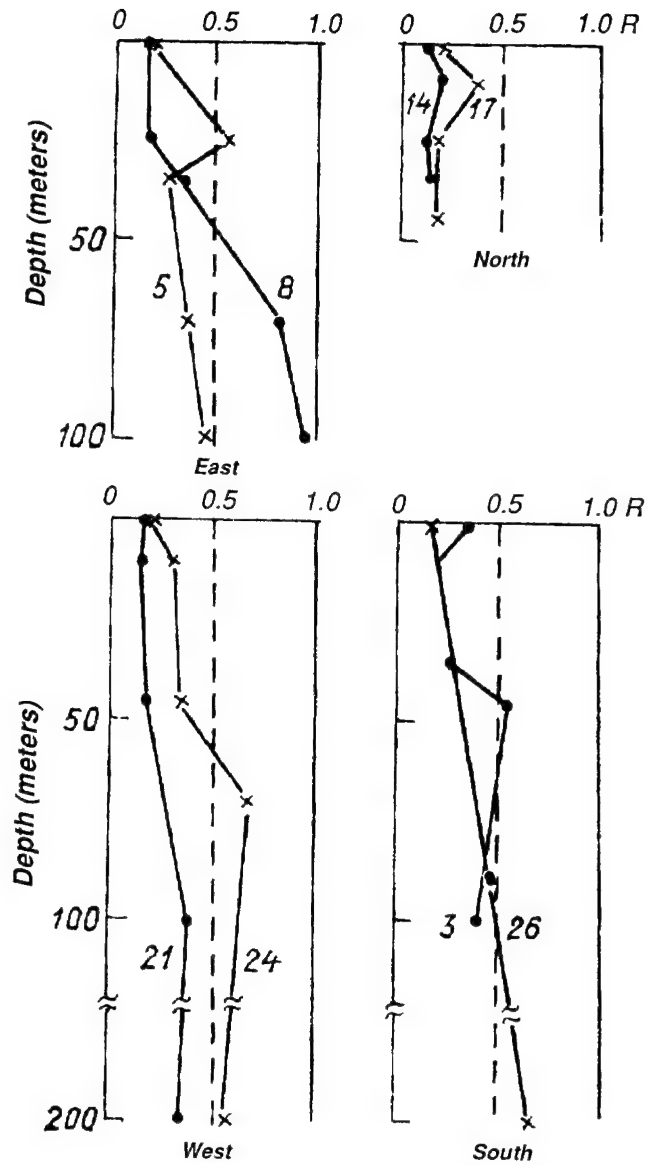

Fig. 1. Vertical distribution of the concentration ratio of thorium^{-234} and uranium^{-238} (R) in the waters of the Bering Sea: a - east polygon, b - north polygon, c - west, d - south.

and approached the level of P_B in the most productive areas of the Bering Sea.

In the South China Sea, determinations of biosedimentation rate were carried out at a multiday station (station 43) at 4-day intervals.

Table 1. *Vertical distribution of the speed of sedimentation for suspended organic substance (P_B) in separate areas of the Pacific Ocean in 1984.*

Station no. (polygons or transects)	Coordinates width	Coordinates length	Depth (m)	Data	Level (m)	P_B (mg C m^{-3} day^{-1})
Station 3 South polygon	53°15'	175°20'	4,000	3.07	0	7.93
					10	17.05
					35	10.41
					45	3.20
					100	5.88
Station 5 East polygon	57°28'	176°00'	2,590	7.07	0	19.64
					25	16.43
					35	6.46
					70	0.90
					100	0.32
Station 8 East polygon	57°08'	173°43'	129	10.07	0	18.34
					25	3.09
					35	10.91
					70	6.85
					100	4.68
Station 14 North polygon	64°21'	171°23'	40	13.07	0	21.40
					10	15.51
					25	22.86
					35	22.13
Station 17 North polygon	63°26'	172°52'	63	15.07	0	15.80
					10	6.02
					25	22.03
					45	18.60
Station 21 West polygon	58°02'	170°01'	1,710	20.07	0	23.64
					10	24.05
					45	19.41
					100	6.22
					200	5.75
Station 24 West polygon	57°29'	170°39'	989	24.07	0	16.76
					10	8.63
					45	7.38
					70	2.00
					200	2.85
Station 26 South polygon	54°14'	177°04'	3,926	26.07	0	20.94
					200	2.20
Station 27	34°59'	144°56	5,778	9.08	0	6.85
					10	10.20
"Kurosio" transect					25	8.97
					45	4.50
					100	3.38

Table 1. *Continued.*

Station no. (polygons or transects)	Coordinates width	Coordinates length	Depth (m)	Data	Level (m)	P_B (mg C m^{-3} day^{-1})
Station 33	31°29'	135°00'	1,890	13.08	0	7.98
					25	3.10
"Kurosio" transect					45	8.63
					100	6.85
					200	6.73
Station 43-1 South China Sea	26°54'	140°59'	1,700	2.09	0	13.65
					25	20.07
					45	25.24
					100	20.07
					200	2.46
Station 43-2 South China Sea	6°59'	141°02'	1,700	6.09	0	20.38
					25	19.06
					45	17.03
					100	9.02
					200	0.72
Station 44 Philippine Sea	20°00'	126°00'	1,500	10.09	0	15.15
					25	9.02
					45	11.22
					100	4.82
					200	0.96

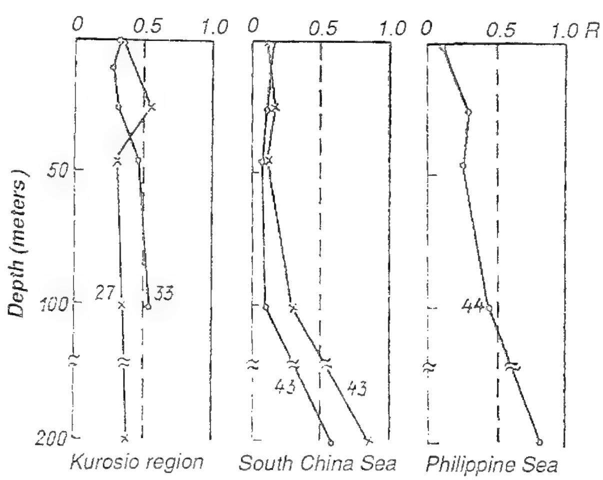

Fig. 2. Vertical distribution of the concentration ratio of $thorium^{-234}$ and $uranium^{-238}$ (R) in the Northwest Pacific ocean: a - Kurosio region, b -South China Sea, c - Philippine Sea.

A redetermination of P_B showed that the biosedimentation rate in the upper 0- to 50-m layer changed insignificantly during the experiment: the general character of the vertical distribution of $thorium^{-234}$ was preserved, and, although at some levels in the upper layers of the water, the biosedimentation rate changed appreciably (by up to 50%), the average rate of removal of suspended organic particles in the 0- to 50-m layer remained at a constant high level, 18.98-19.43 mg C m^{-3} day^{-1} (Tables 1 and 2).

In addition to determinations of biosedimentation at individual levels, the average rates of removal of organic matter were calculated totally for the 0-45, 45-100, and 100- to 200-m levels (Table 2). At all stations of the area studied, the highest rate of the biosedimentation process was observed in the upper 45-m layer. With depth, under the thermocline layer, P_B decreased

Table 2. *Average rate/speed of biosedimentation (P_B = mg C m^{-3} day^{-1}) at various levels of euphotic zones.*

Station no.	Layer (m)					
	0-45	0-100	45-100	45-200	100-200	0-200
3	11.92	7.86	4.54	--	--	--
5	13.82	7.12	1.64	--	--	--
8	9.80	8.23	6.92	--	--	--
14	20.33	--	--	--	--	--
17	16.13	--	--	--	--	
21	22.20	17.04	12.80	8.40	6.00	11.50
24	9.01	5.86	3.28	2.96	2.53	4.19
26	18.83	16.25	14.15	9.46	6.85	11.57
27	8.08	5.80	3.94	--	--	--
33	5.69	6.81	7.74	7.13	6.79	6.80
43-1	19.43	21.20	22.65	15.30	11.26	16.23
43-2	18.98	15.70	13.02	12.03	4.87	10.28
44	11.21	9.45	8.02	4.71	2.89	4.66

sharply, by a factor of 3-5 in comparison with surface waters. In the 70- to 200-m layer, the biosedimentation rate P_B changed insignificantly. The maximum values of the integrated indices of the biosedimentation rate were obtained for a series of stations of the north (stations 14, 17) and south (station 21) polygons, where the biosedimentation rate was found to be stable and high during the study period at individual levels within the confines of the euphotic zone. At station 26 of the south polygon, where the rates of removal of organic matter were calculated from the results of measurements of thorium^{-234} concentrations at the 0 and 200-m levels only, the integrated indices were found to be at an equally high level. The calculations were based on the assumption of linear change of the index with depth. Assuming the character of the vertical distribution of the biosedimentation rate to be common to all the other stations of the Bering Sea (i.e., a sharp drop in P_B under the thermocline layer), one must consider the calculated values of the integrated index of the biosedimentation rate at station 26 to be somewhat understated in the 0- to 45-m layer and overstated by at least 20% for the 45- to 200-m layer (Table 2).

Earlier, in June 1981, determinations of the biogenic sedimentation rate in approximately the same areas as in 1984 were carried out in the Bering Sea. A comparative analysis of the data obtained makes it possible to draw certain preliminary conclusions about the characteristics of the biosedimentation processes in the pelagic zone of the Bering Sea. Because of the absence of data on the seasonal dynamics of these processes, the identified characteristics can only be extended to certain biological seasons and individual stages of succession of the ecosystems of the areas studied.

In 1981 and 1984, the studies were conducted during the spring-summer period, when the plankton communities were in the productive phase of development and were characterized by a high rate of regeneration of organic matter; the primary production level in the Bering Sea during this period was comparable to the value of this index in the most productive areas of the World Ocean (Korsak 1987). The high rate of regeneration of organic matter in the euphotic layer of the sea determined the rate of the biosedimentation processes; the flow of organic particles from the upper 100-m layer in 1981

ranged, in different areas of the Bering Sea, from 175 to 760 mg C m^{-2} day^{-1}, and in 1984, from 586 to 1,704 mg C m^{-2} day^{-1}. In 1984, in the entire water area studied at individual polygons, on the average, the biosedimentation rate was 1.5-3.0 times that in 1981. Despite appreciable year-to-year differences in rates of removal of organic matter, a largely similar pattern of distribution of P_B values in both depth and water area of the sea was observed.

The results obtained make it possible to distinguish areas in the Bering Sea where the biosedimentation rate remains at a constant high level from year to year. Such areas include primarily the shoal off St. Lawrence Island (polygon II in 1981 and north in 1984). Almost equally high values of P_B were noted in the southern portion of the sea (polygon IV in 1981 and south in 1984). Obviously, the magnitude of the P_B values is closely related to the structural-functional characteristics of the ecosystems of the upper production layer. However, determining the relationship of these processes requires special studies at multiday stations with parallel determination of the dynamics of the ecosystem that influence the magnitude of P_B. The uranium-thorium method makes it possible to obtain indices of biosedimentation rate averaged over a period of 5-72 days (Zesenko and Yegorov 1987).

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SEDIMENT HYDROCARBONS IN THE BERING SEA

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Introduction

The distribution, sources, and fate of natural and anthropogenic hydrocarbons in polar regions are poorly understood. As increased exploration and development of oil and gas reserves in polar regions continue, an understanding of the hydrocarbon geochemistry in these areas becomes essential. A preliminary study to assess baseline sediment hydrocarbon levels and distributions, sources (including biogenic, anthropogenic, and natural seepage), and potential pathways of hydrocarbon transport was undertaken by Venkatesan and Kaplan (1982) on the outer Continental Shelf of Alaska. Sediment samples from the Beaufort Sea, southeastern Bering Sea, Norton Sound, Navarin Basin, Gulf of Alaska, Kodiak Shelf, and lower Cook Inlet were collected and analyzed. The researchers concluded that these areas exhibit little evidence of petroleum hydrocarbons except at a few isolated locations. The sediments contain mixed marine autochthonous and terrestrial allochthonous hydrocarbons. A complex mixture of polynuclear aromatic compounds, attributed to pyrolytic sources, were detected at all sites. Samples from one station in lower Cook Inlet and one in the southeastern Bering Sea indicated the presence of weathered petroleum.

The present study is intended to determine the concentrations, distributions, and sources of hydrocarbons in the central and western Bering Sea. Sediment samples were obtained from gravity cores (single samples and profiles) during a joint U.S.-U.S.S.R. expedition on the RV *Akademik Korolev* during July 1984. Station locations are shown in the frontispiece.

Methods

Kennicutt et al. (1988) and Brooks et al. (1986) described the analytical methods used in this study. Briefly, sediment samples were freeze-dried, Soxhlet-extracted for 12 hours (hexane), and analyzed. Polynuclear aromatic hydrocarbons were detected by spectrofluorescence on a Perkin-Elmer 650-40 fluorometer. Extracts were then analyzed for aliphatic hydrocarbons by gas chromatography with flame ionization detection. Component separations were attained by using fused-silica capillary columns (DB-5) and temperature programming. Selected sediments were further analyzed by gas chromatography and mass spectrometry (HP 5890/HP5790 MSD) in both scanning and selected-ion monitoring modes.

Results and Discussion

For ease of discussion, stations have been grouped according to geographical location as follows (Fig. 1): East - stations 5, 6, 7, 8, 9, 10; North - stations 11, 12, 13, 14, 15, 16, 17, 18, 19; West - stations 20, 21, 22, 23, 24; South - stations 1, 2, 3, 4, 25, 26.

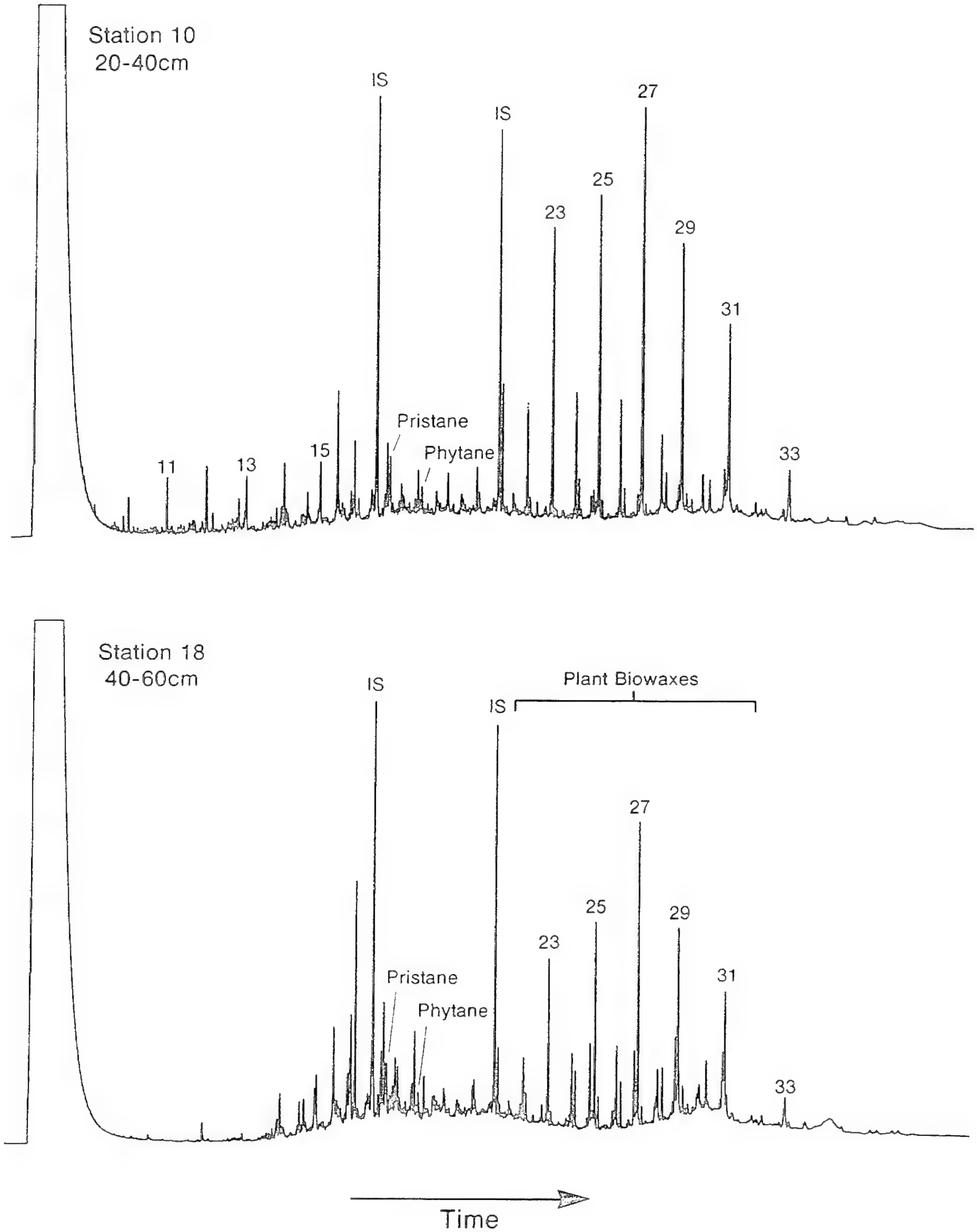

Fig. 1. Selected representative gas chromatographic patterns for the central and northwestern Bering Sea.

Hydrocarbons

Selected hydrocarbon parameters are summarized in Tables 1 and 2. On average, the highest sediment hydrocarbon concentrations were at stations in the southern and western Bering Sea. The average concentrations for the southern Bering Sea are elevated due to one sample at the bottom of core 25 that contains anomalously high hydrocarbon levels (Table 2). All stations had significant amounts of higher molecular weight hydrocarbons attributable to terrigenous plant biowaxes (normal alkanes with 23-33 carbons). This is evidenced by the high carbon preference index (av. CPI 3.8-5.0) and the predominance of long-chain ($\geq C_{23}$) odd-carbon-numbered alkanes over shorter chain ($<C_{23}$) normal alkanes (Table 1). Pristane was generally the dominant isoprenoid, but there are numerous locations where phytane exceeded pristane (Fig. 1). Aliphatic-hydrocarbon concentration ranges and averages were similar to those published for other Bering Sea and Alaskan locations (Tables 1 and 2). The higher CPI and n-alkane ratios at the central and northwestern Bering Sea stations suggest either a greater influx of organic matter from terrestrial sources or an increased input of lower molecular weight, low-CPI hydrocarbons (petroleum) in the south and west. Petroleum-related hydrocarbons were particularly evident at stations 20, 24, and 25, favoring the latter explanation (Fig. 2). Hydrocarbon levels were substantially elevated at the southern and western stations as compared to the "background" levels at the central and northwestern stations.

Fluorescence analyses confirmed the previous observation that polycyclic aromatic hydrocarbons (PAH's) were present at all locations. The lowest levels were again present

Table 1. *Summary of various hydrocarbon parameters by region for the Bering Sea.*

Parameter	West	South	East	North
n =	24	10	12	17
Fluorescence				
Maximum intensity	1,279	934	260	62
Ratio R1	3.33	1.23	2.27	3.63
Maximum EX	325	311	334	339
Maximum EM	364	351	373	373
Gas chromatography				
ΣUCM (ppm)	20	73	11	12
UCM $<n\text{-}C_{23}$ (ppm)	8	24	4	4
UCM $>n\text{-}C_{23}$ (ppm)	12	49	7	8
$\Sigma n\text{-}C_{15}$ $n\text{-}C_{32}$ (ppm)	4.1	4.6	2.6	2.9
Prix/Phyt	2.2	1.0	2.0	1.2
CPI 4.0	4.0	3.8	5.0	4.8
$\frac{\Sigma n\text{-}C_{15} \text{ to } n\text{-}C_{22}}{\Sigma n\text{-}C_{23} \text{ to } n\text{-}C_{32}}$	4.4	3.0	6.5	6.5

Table 2. *Summary of ranges of various hydrocarbon parameters for this study and the historical data base (after Venkatesan and Kaplan 1982 and this study).*

	Total hydrocarbons[a] (ppm)	Resolved n-alkanes (ppm)	n-alkane maxima	odd[b]/even	Pristane/Phytane
This Study					
East	5-25	1.1-4.3	27 or 31	2.6-12.0	0.7-8.0
North	5-28	1.5-8.9	27, 29, or 31	2.8-7.3	0.4-2.9
West	5-45	1.6-7.3	15, 27, 29 or 31	2.4-5.32	0.7-9.7
South	7-37 (591)[c]	0-6.4 (24.7)[c]	15, 27, 29 or 3		
After Venkatesan and Kaplan (1982)					
S.E. Bering Sea	1.9-29.0	0.3-2.9	22, 27, or 29	1.8-4.0	2.0-5.8
Navaren Basin	2.4-52.0	0.25-2.6	27	3.5-4.8	----
Gulf of Alaska	1.5-26.0	0.06-2.0	22, 27, or 29	1.0-2.5	1-7.0
Kodiak Shelf	0.9-18.0	0.01-0.80	27 or 29	0.8-2.8	2-6.4
Cook Inlet	0.9-39.0	<0.01-3.6	27 or 29	0.9-5.9	1-6.7
Norton Sound	1.9-29.0	0.01-5.4	27	1.7-6.3	1-8.0
Beaufort Sea	20.0-50.0	1.4-5.0	27 or 29	1.8-5.0	1.5-2.5

[a]This study - UCM; other - g.c. derived
[b]This study - sum from C_{23} to C_{32}, other sum from C_{15} to C_{34}
[c]One extremely high value

at the east and north stations (Fig. 3). The high levels of petroleum-related fluorescence in the western Bering Sea sediments were typical of a middle range American Petroleum Institute (API) gravity oil (30°-45°) while the petroleum at station 25 was more typical of a condensate (API >45°). This interpretation is confirmed by the gas chromatographic analysis, where a low-molecular-weight envelope of hydrocarbons with a maximum at n-C_{13} is apparent (Fig. 2). Isoprenoids with 11-20 carbons, typical of petroleum, are also present. In contrast, the petroleum hydrocarbons detected at stations 20 and 24 have a much broader distribution skewed toward higher molecular weight compounds (Fig. 2). Perylene was detected at many locations (Fig. 3).

At six locations, variations in hydrocarbon parameters with depth were determined (Figs. 4-7). Stations from the central and northwestern Bering Sea had low-level monotonous hydrocarbon distributions with depth (Fig. 4). At stations from the south and western Bering Sea, increases in fluorescence intensity with depth were particularly dramatic (except station 21; Fig. 5). The bottom section at station 25 had the highest values measured. Hydrocarbon ratios were also relatively monotonous or erratic with depth for the central and northwestern locations, indicating a relatively constant concentration and composition of hydrocarbon inputs (Fig. 6). At stations 21 and 24, CPI and the ratio of normal alkanes <n-C_{23} to >n-C_{23} decrease with depth as a result of increasing amounts of petroleum (Fig. 7). These vertical trends suggest that the petroleum hydrocarbons observed at stations 21, 24, and 25 are derived from petroleum seepage and not pollution from the overlying

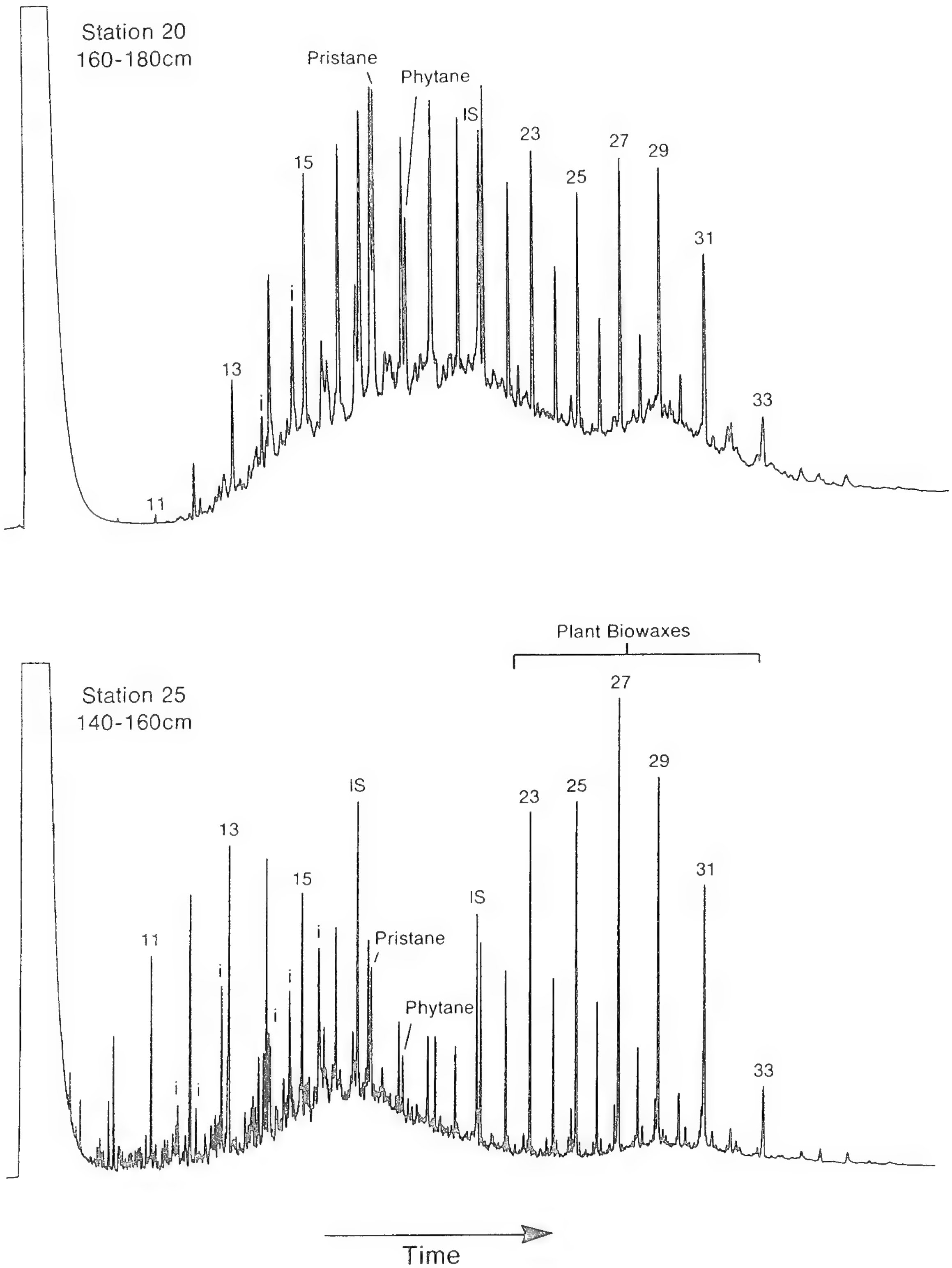

Fig. 2. Selected gas chromatograms illustrating the presence of petroleum hydrocarbons at southern and western Bering Sea locations.

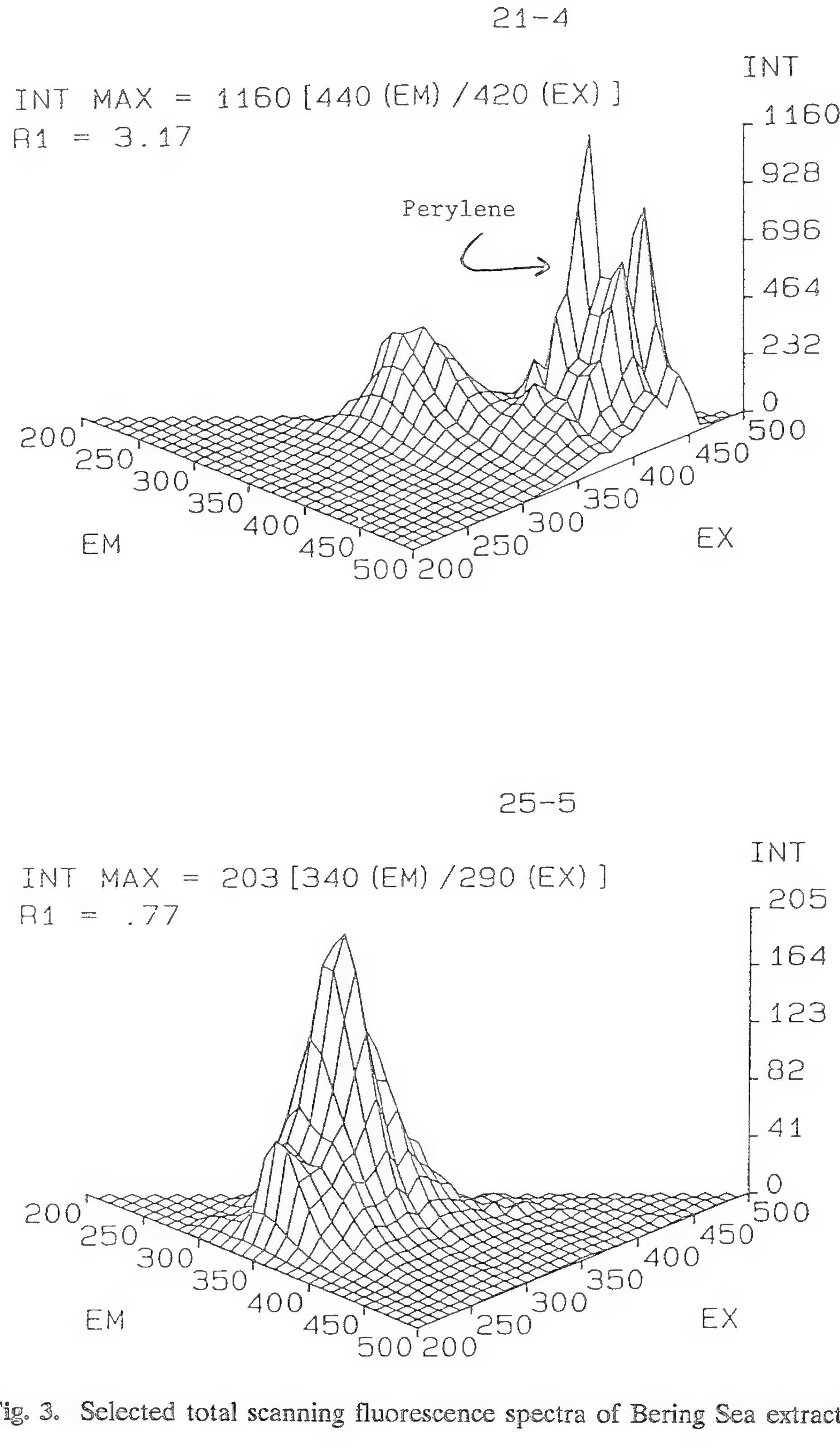

Fig. 3. Selected total scanning fluorescence spectra of Bering Sea extracts.

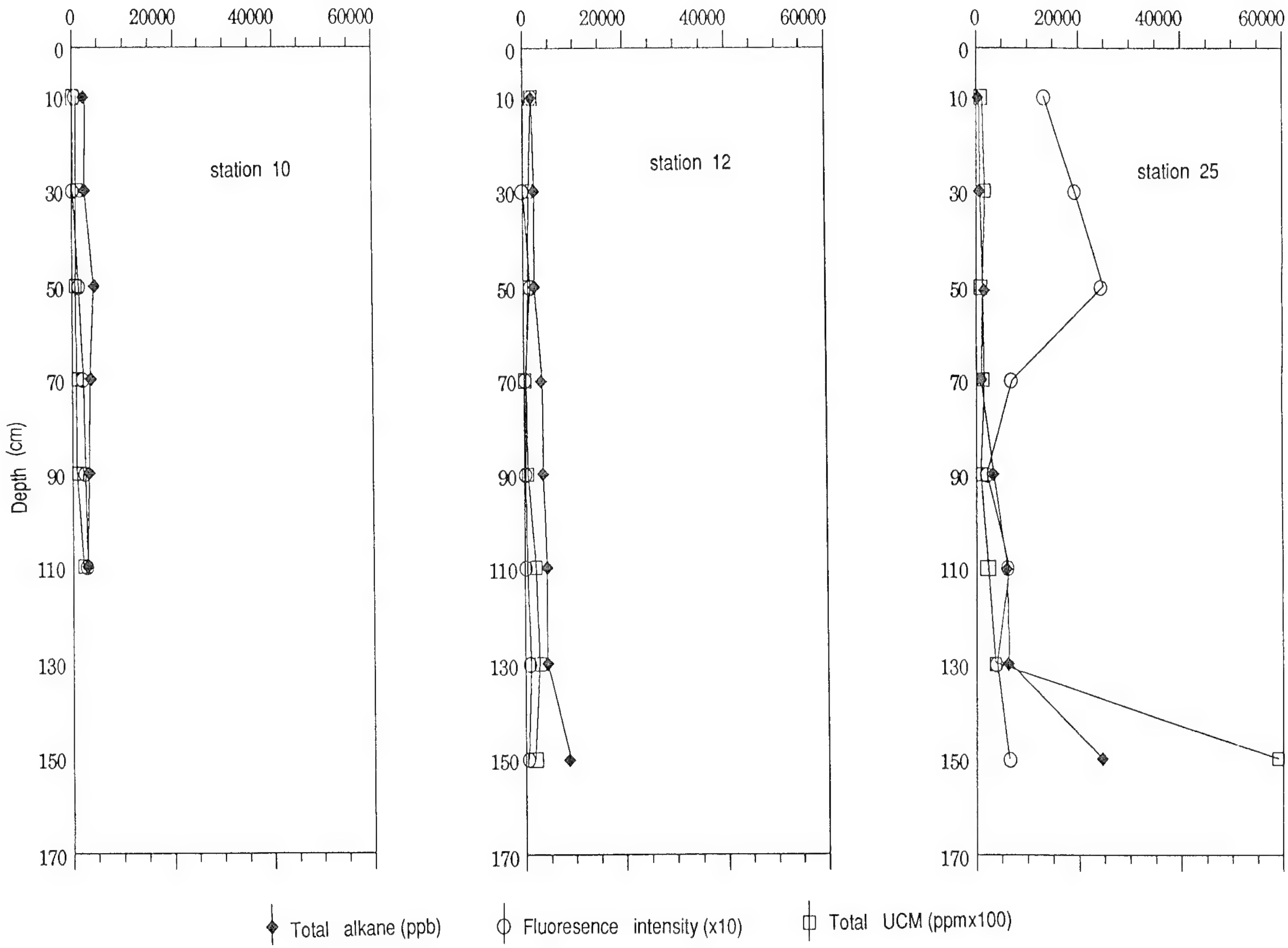

Fig. 4. Distribution of selected hydrocarbon parameters at stations 10, 12, and 25.

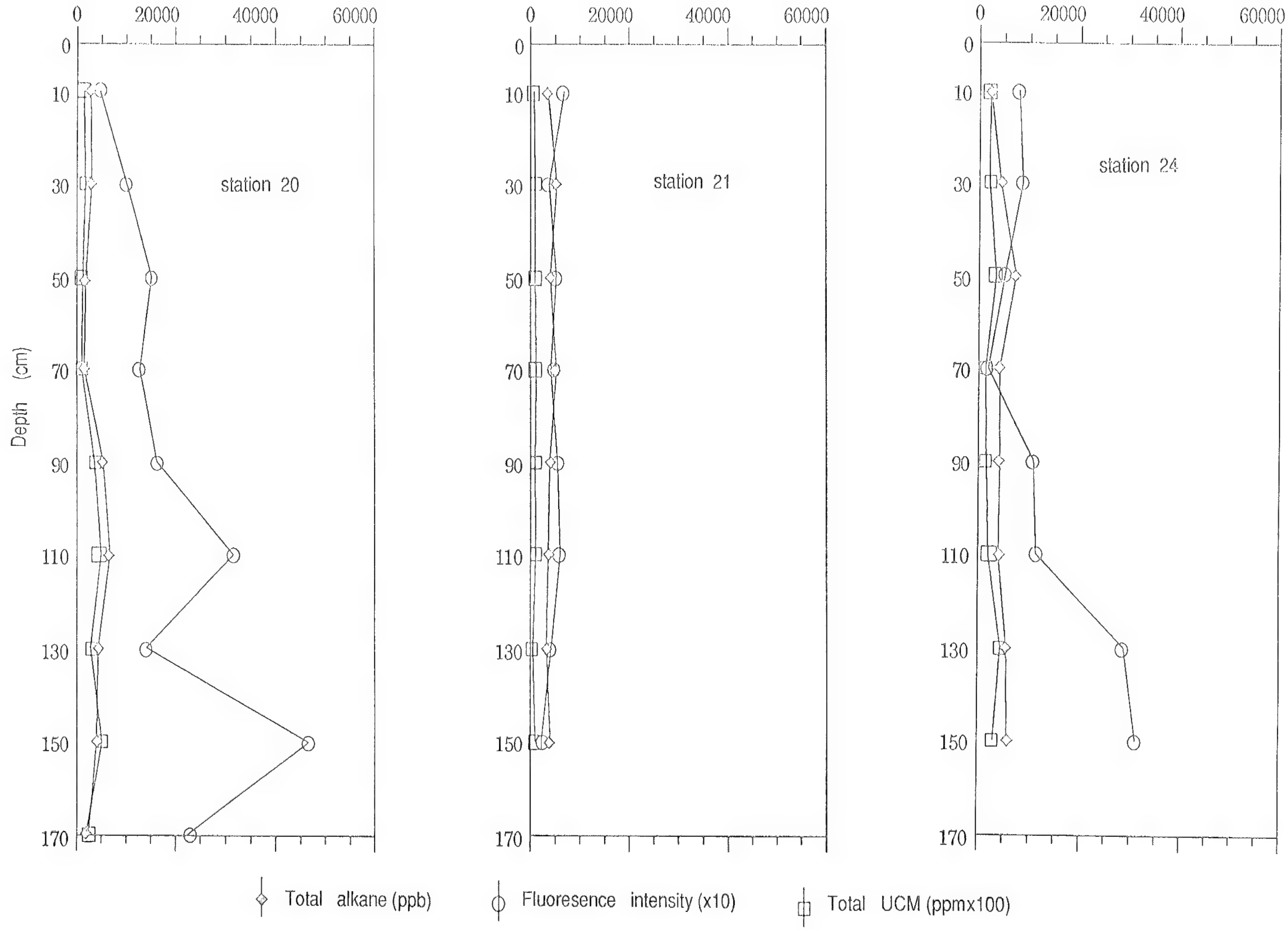

Fig. 5. Distribution of selected hydrocarbon parameters at stations 20, 21, and 24.

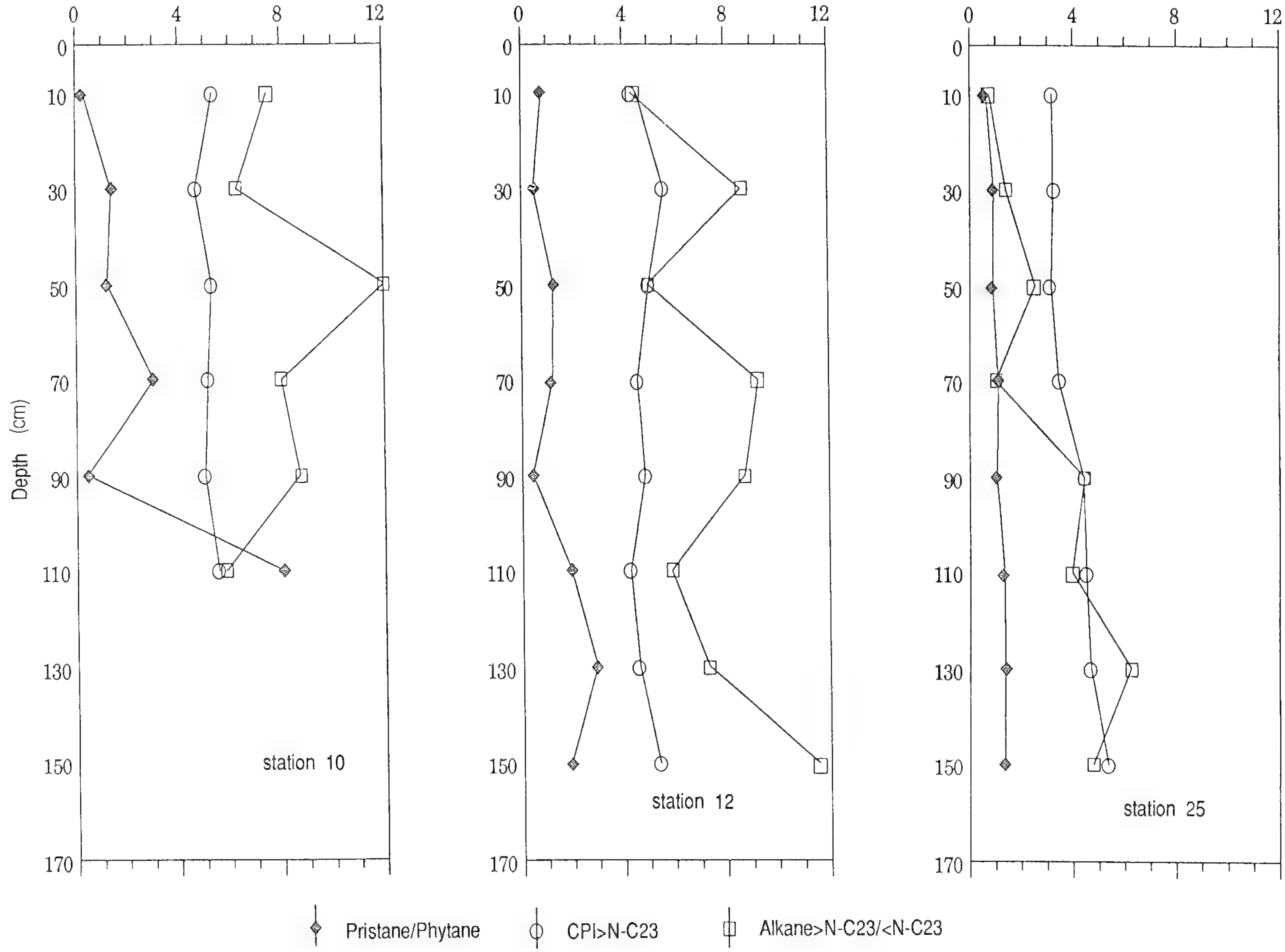

Fig. 6. Distribution of selected hydrocarbon ratios at stations 10, 12, and 25.

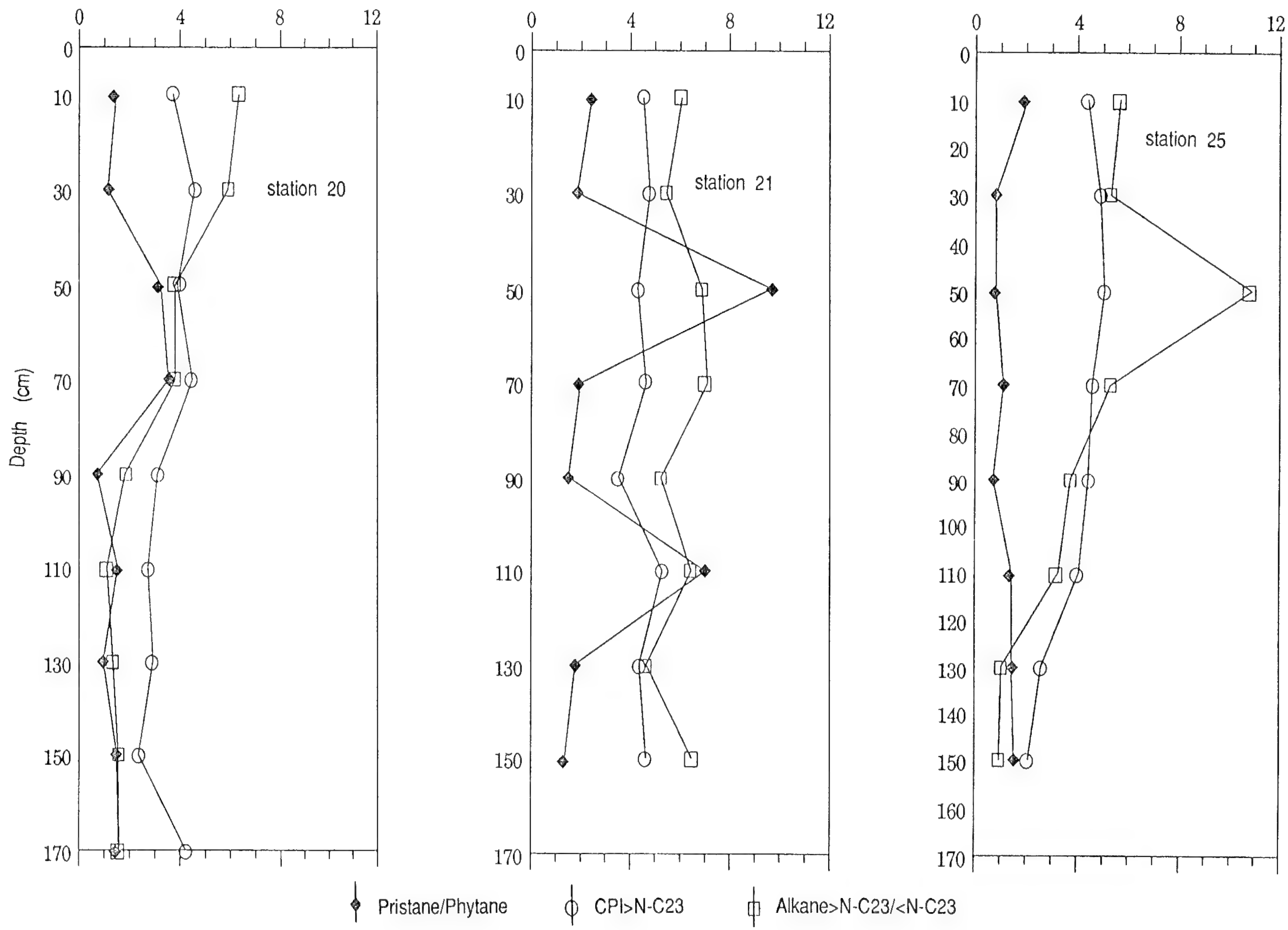

Fig. 7. Distribution of selected hydrocarbon ratios at stations 20, 21, and 24.

water column. Background PAH's composed primarily of nonalkylated analogues have previously been suggested to have a pyrogenic source in the eastern Bering Sea. This observation is consistent with the low levels reported here for central and northwestern locations (Venkatesan and Kaplan 1982). In contrast to this, highly alkylated homologous series of aromatics indicative of unprocessed petroleum were detected at the suspected oil-seep locations (Fig. 8).

Biological Markers

The previous report of the presence of significant amounts of unique aliphatic hydrocarbon in the eastern Bering Sea was confirmed (Venkatesan and Kaplan 1982). Many of the sediment extracts contain compounds previously identified as olefins. A tetraene (Kovats Index (KI) = 2,657), squalene (KI = 2,895), and a C_{30} bicyclic tetraene (KI = 3,027) were attributed to inputs from zooplankton or phytoplankton (Venkatesan and Kaplan 1982). These compounds were present at all locations, though concentrations vary widely. A suite of hopenes, moretanes, and $\beta\beta$-hopanes were present at four locations analyzed and appeared to represent a background biological-marker mixture (Fig. 9). This mixture is indicative of immature sediments, but is more mature than very recent biolipids, as evidenced by the presence of $\beta\beta$-hopanes and $\beta\alpha$- hopanes. This background may represent erosionally exposed in-place sediments or material from surrounding land masses that has been transported to the site of deposition. The precursor functionalized hopanoids and steroids representative of unaltered biolipids are not determined by the analytical methods used in this study. The detected compounds most likely represent early alteration products of biogenic lipids of bacterial or algal origin. In contrast to these immature markers, overprinting by 17α-, 21β-hopanes is evident at the sites suspected of containing mature migrated petroleum. These mature biomarkers, which are only produced when temperatures are substantially higher than in these near surface sediments, are present in extracts from stations 20, 24 and 25 (Figs. 9 and 10). The presence of these compounds confirms that the in situ biological or "recycled" immature lipids are overprinted with mature petroleum hydrocarbons derived from a much deeper, higher temperature source.

Conclusions

Aliphatic and aromatic hydrocarbons were detected at all locations sampled in the Bering Sea. The hydrocarbons are a mixture of marine biological debris (bacteria, algae, zooplankton, phytoplankton), terrestrial plant biowax (normal alkanes), "recycled" or exposed immature sediments, petroleum (natural seepage), and pyrolytic sources. The levels of hydrocarbons detected were similar to previously reported studies of the Alaskan outer Continental Shelf. Unique biological olefins, previously identified in the area, were widely distributed. The relative amounts and composition of hydrocarbons varied widely over the area sampled. The presence of a complete suite of normal alkanes and isoprenoids, an unresolved complex mixture, petroleum-related PAH's, mature biological markers (hopanes), and vertical distributions of hydrocarbons confirm the presence of petroleum at stations 20, 24, and 25. This petroleum is most likely derived from natural seepage from much deeper source rocks and reservoired fluids. The petroleum seepage at station 25 is typical of a condensate and is significantly different from that observed at the western stations.

The preservation of relatively labile biological compounds within sediments suggests that hydrocarbons introduced by human activity would persist in the environment. Some locations have apparently already been exposed to natural seepage of hydrocarbon and may represent a unique in situ laboratory to study the effects of hydrocarbon exposure on ecosystems and benthic ecology in polar regions.

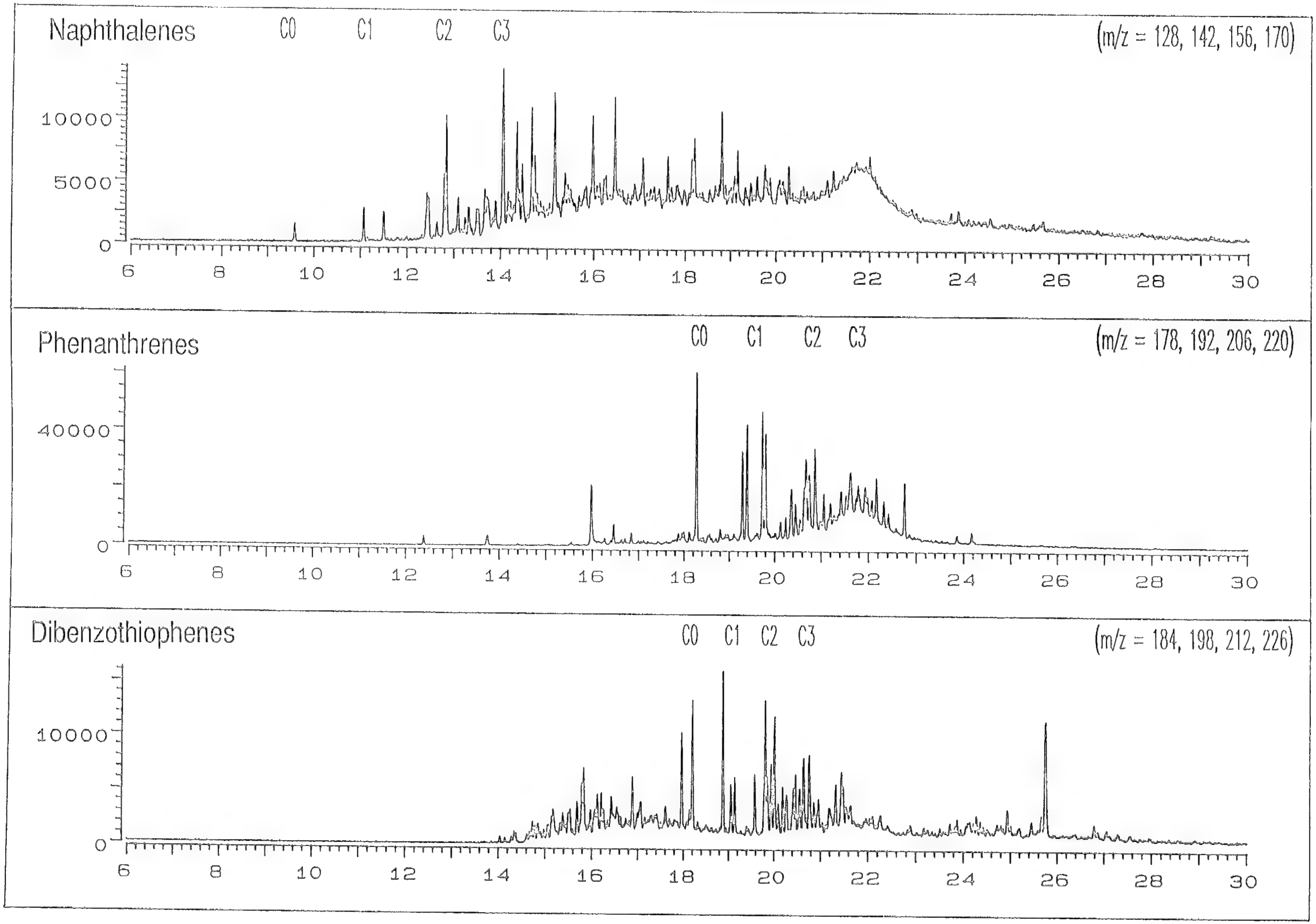

Fig. 8. Distribution of naphthalenes, phenanthrenes and dibenzothiophenes at station 20.

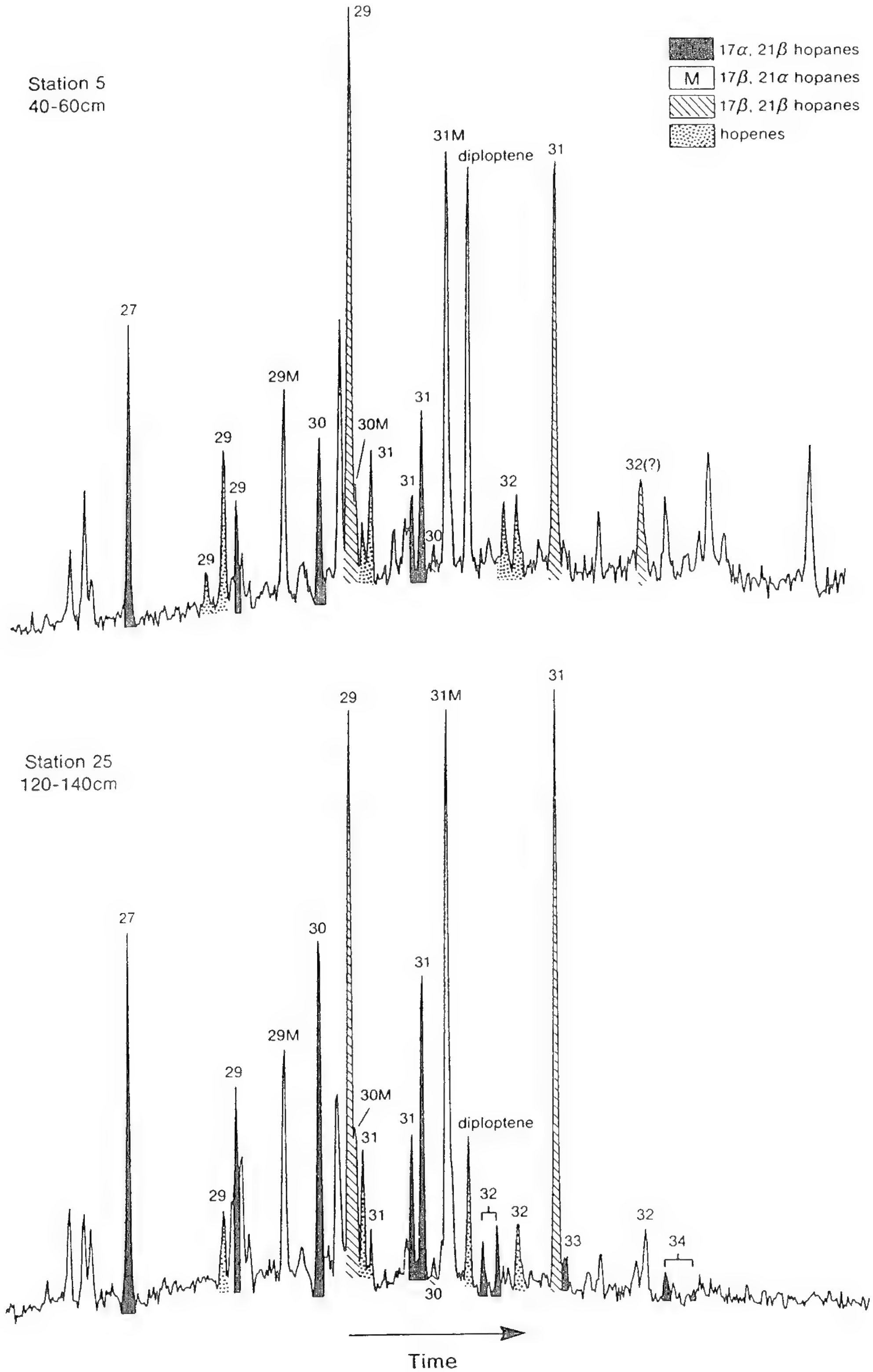

Fig. 9. Distribution of biological marker compounds at stations 5 and 25 (M/Z = 191).

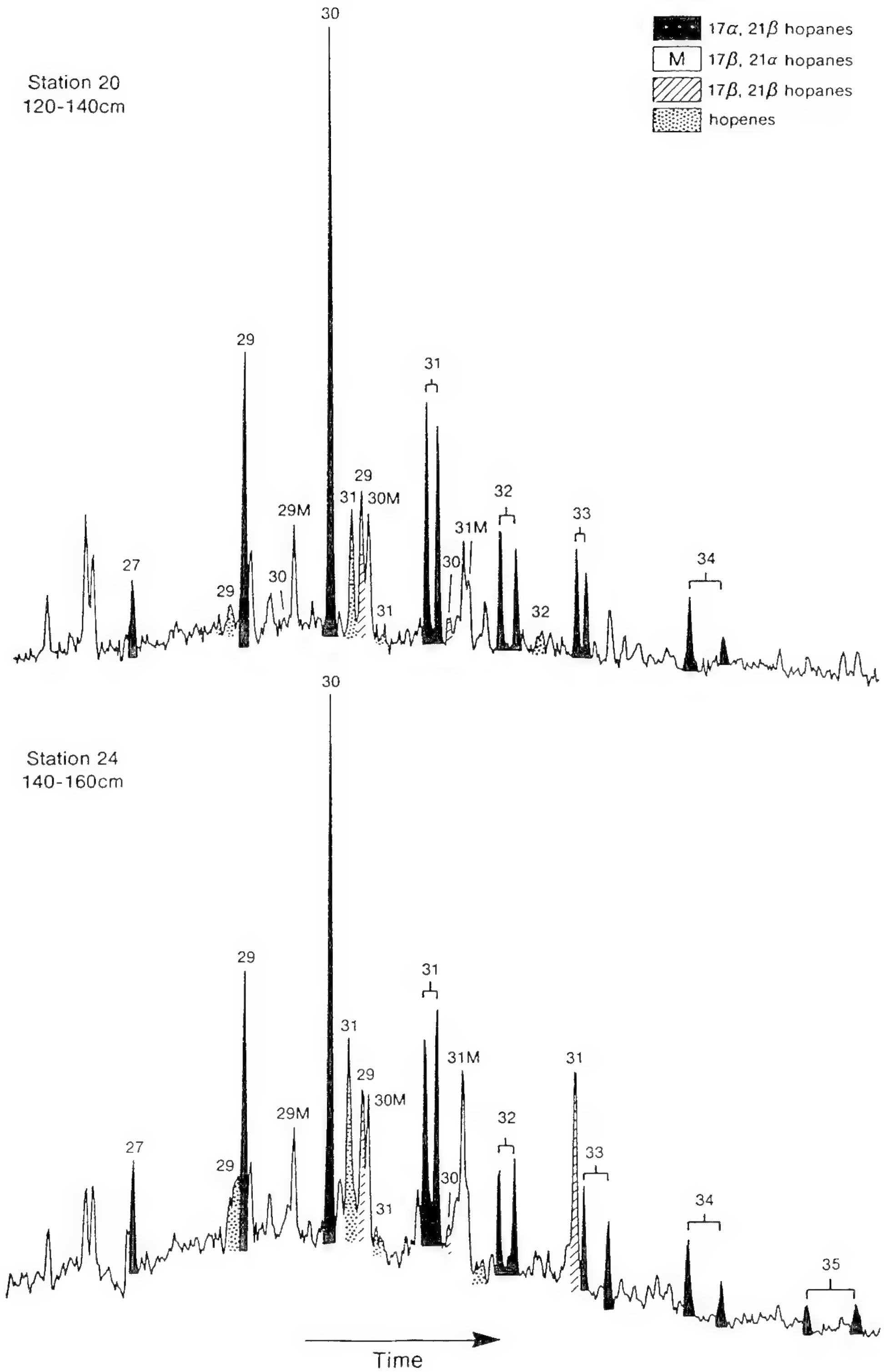

Fig. 10. Distribution of biological marker compounds at stations 20 and 24 (M/Z = 191).

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Biotoxicology

STUDY OF THE COMBINED ACTION OF CERTAIN POLLUTANTS ON MARINE PHYTOPLANKTON UNDER MICROCOSM CONDITIONS

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To predict the ecological aftereffects of environmental pollution and estimate the critical concentrations of pollutants, in addition to conducting observations of the background levels of biological processes, it is also necessary to carry out active model experiments with microcosms (Maksimov and Fedorov 1969; Patin 1979; Izrael and Tsyban 1981; Korsak et al., n.d.). In conducting experiments with natural populations of aquatic organisms under conditions approximating nature as closely as possible, it is necessary to consider that the degree and character of the joint action of pollutants may differ appreciably from the effects of their separate influence (Maksimov and Fedorov 1969; Korsak and Yegorov 1985; Korsak et al., n.d.). Therefore, such experiments should be carried out under strictly controlled conditions by means of mathematical planning methods that make it possible to allow for different variations of the interactions between the factors studied and the responses of the biological system (Maksimov and Fedorov 1969).

At the present time, much more is known about the effect of various pollutants on individual species of algae and aquatic organisms under laboratory conditions than about their influence on natural plankton (Leland et al. 1974; Overnell 1975; Filenko and Khobotyev 1976; Patin 1979). Information on the action of metals on natural plankton communities is of major interest for biological monitoring, but obtaining the necessary information involves considerable difficulties of a practical nature. Use of model bodies of water for setting up experiments under conditions approximating nature has shown that the influence of the so-called capacity effect on the course of biological processes in microcosms can be avoided only when the volumes of water exceed 2,000 m^3 (Overnell 1975). Conducting the experiments with such large volumes of water involves enormous expenditures on equipment, complicating the conduct of the work. Use of microcosms of comparatively large volumes in solving this problem leads to a reinforcement of the capacity effect, although it does not reduce their value for ecological toxicology if during the analysis of the results obtained, the changes that took place in the ecosystem under action of pollutants are considered in relation to a control variant. An advantage of this approach is that the results obtained in the experiments usually exhibit a higher statistical reliability than do analogous data obtainable from field observations. The purpose of the studies described, conducted during the cruises of the RV *Akademik Shirshov* and *Akademik Korolev* in 1981 and 1984 in the Bering Sea and certain areas of the northwestern Pacific Ocean, was to study the influence of certain pollutants on the functioning of isolated plankton communities under microcosm conditions. Since it is impossible to determine in advance the

characteristics of the reaction of a plankton community to the studied pollutants in areas exposed to anthropogenic influences and relatively clean areas, of greatest interest from our point of view was a comparative study of the responses of various communities isolated from ecosystems subjected to different degrees of anthropogenic load.

Materials and Methods

Any complex ecological system whose behavior depends on the total number of factors and on the interactions between them should be studied by taking into account the manifestation of its properties as a whole with the aid of special mathematically grounded techniques and methods. Such approaches provide for the possibility of simultaneous and independent investigations of the influence of a selected set of pollutants on the structural and functional characteristics of the system studied.

The most complete description of a response surface reflecting the characteristics of the combined influence of the factors studied is obtained by using the plans for a complete factorial experiment, which are based on the realization of all possible combinations (N) of the factors studied, each of which is examined at several levels (Maksimov and Fedorov 1969).

It is these kinds of plans of the CFE 3^2 experiment that we used in setting up tests for studying the reaction of a plankton community to the combined action of certain pollutants. The experimental setup provided for performing nine different variants of the experiment simultaneously, eight of which involved adding the pollutant studied; the ninth was the control (Table 1).

The action of the pollutants in the experiments was estimated from the change in the numbers and biomass of microzooplankton and in the values of primary and bacterial production of organic matter.

Experiments to study the combined action of the widely distributed and comparatively little-known toxic pollutants $ZnCl_2$, $CdCl_2$, PCB, and benzo[a]pyrene on the plankton community were carried out in nine aquariums that were filled with 18 liters of seawater from the upper half-meter layer. In all the experiments, the aquariums were thermostated in a bath with circulating outside water. The duration of the Bering Sea experiments was 4-5 days, since an isolated plankton community can exist for only a short time.

The samples for determining the primary and bacterial production and the numbers of infusorians and flagellates were taken when the experiments were set up and also on the third and fifth days from the start of the test. In some tests, the numbers of protozoans were taken into account on the second and fourth days.

Salts of the metals cadmium and zinc, as well as solutions of PCB and benzo[a]pyrene, were added to the aquariums in accordance with the CFE 3^2 (Tables 1 and 2). The primary production of organic matter was determined by using a radiocarbon modification of the flask method (Korsak and Yegorov 1985). The exposure time in all the Bering Sea experiments in the determination of primary and bacterial production was 24 hours. The bacterial production was determined from the dark assimilation of CO_2, using a method proposed by V.I. Romanenko (Korsak et al., n.d.). The samples for determining the primary and bacterial production were filtered on Synpor No. 7 membrane filters. The calculation of the radioactivity of filters with ^{14}C-labeled phytoplankton and bacterioplankton was carried out with a Mark-2 Nuclear Chicago Scintillation counter using ZhS-106 and ZhS-8 scintillators (Korsak and Yegorov 1985).

Quantitative and qualitative estimation of the colorless forms of flagellates and infusorians was carried out in concentrated and nonconcentrated water samples in a box-type

Table 1. *Influence of cadmium and zinc on the total number of infusoria N_1, (in thousands of specimens/L) and the total number of flagellates N_2 (in millions of specimens/L).*

			Experiment 1					Experiment 2				
Day of experiment			1st	3rd	4th	3rd	4th	1st	3rd	1st	3rd	5th
Variable no.	Cd (mg/L)	Zn (mg/L)	N_1	N_2	N_2	N_1	N_1	N_2	N_2	N_1	N_1	N_1
1	trace	trace	0.12	1.4	1.00	0.76	1.00	1.90	2.60	0.60	1.10	0.84
2	0.025	trace	0.20	1.70	1.00	1.60	1.20	0.56	0.08	1.00	0.14	0.28
3	0.050	trace	0.16	2.00	1.70	1.70	0.90	0.20	0	0.67	0.16	0.12
4	trace	0.25	0.08	1.00	0.60	1.20	0.60	0.72	0.24	0.67	0.10	0.76
5	0.025	0.25	0	1.30	0.70	1.40	0.50	1.20	0.60	0.58	0.07	0.22
6	0.050	0.25	0.08	1.40	1.00	1.20	0.20	0.64	0	0.62	0.26	0
7	trace	0.50	0	1.60	0.40	0	0	0.60	0.64	0.82	0.17	0.70
8	0.025	0.50	0.08	1.20	0.80	0	0	0.52	0	0.91	0.33	0.02
9	0.050	0.50	0.08	0.90	0.70	0	0	0	0	1.50	0.05	0

Table 2. *Combined influence of additions of cadmium and zinc on the primary (P_g=µg C L^{-1} day^{-1}) and bacterial production (P_β=µg C L^{-1} day^{-1}) on the third day of experiments carried out in the Bering Sea.*

Experiment no.	1		2		3	4
Variable no.	P_g	P_β	P_g	P_β	P_g	P_g
1	25.4	2.4	66.7	1.3	30	48.3
2	12.7	7.0	83	1.5	12	32
3	17.0	8.2	36.7	1.7	10	30.7
4	17.5	8.2	46.7	2.6	7	25.1
5	15.5	5.3	63.3	2.8	25	23.1
6	21.5	8.2	70	3.1	11.5	34.6
7	13.0	1.2	66.7	2.2	30	21.8
8	12.0	1.1	69.3	1.5	5	31.0
9	12.2	4.4	56.7	1.6	15	30.3

camera. The water samples were concentrated by reverse filtration, using a sieve with a pore size of 10-15 µm. The flagellates were estimated under an "Amplival" microscope with a magnification of 110 x in phase-contrast illumination. The infusorians were counted under a binocular. From 3 to 50 visual fields were examined in each sample.

The regression coefficients in the equations describing the action of the studied pollutants on the numbers of infusorians and flagellates, as well as the values of primary and bacterial production, were calculated in accordance with a scheme proposed by Margolin (Maksimov and Fedorov 1969). The reliability of the regression coefficients was checked by Daniel's method (Maksimov and Fedorov 1969). On the basis of the calculated regression equations, three-dimensional graph response surfaces that clearly illustrate the characteristics of the combined action of the studied pollutants on the selected biological parameters were plotted.

Results of the Studies

Experimental study of various biological systems is complicated by the fact that the number of factors on which they significantly depend is fairly large, and the types of dependence are known for only a small number of these factors. Another complicating aspect is the presence of interactions between the factors studied, which precludes the possibility of using linear models. The mutual influence of the factors should be discussed if the reaction of the studied system to a given change in any given substance studied depends on the values of another or other elements studied. If there are no interactions between two or more factors, then each of them acts independently, and so the overall effect will be additive. However, additive actions are fairly rare in nature, and therefore it becomes necessary to use the methods of mathematical planning of the experiment, which make it possible, under strictly controlled conditions, to study the simultaneous action of several factors and quantitatively allow for the interactions between them (Maksimov and Fedorov 1969). The study of any biological system may be represented as a study of a function of many variables, that is, finding a dependence of the

$$Y = f(x_1, x_2, x_3, \ldots x_n) \qquad (1)$$

type where Y is the process characteristic being studied and $x_1, x_2, x_3, \ldots x_n$ are the factors on which this characteristic depends.

Since the true form of the function is quite often unknown, an equation that is an expression of this function as a power series is often used to describe the response surface (Maksimov and Fedorov 1969). This equation describes a certain hypersurface in multidimensional space, the study of which may be represented as a study of the shape of the surface called the response surface. In the study of a single-factor dependence, the nonlinearity of the function is due to the appearance of higher than first-power terms in the equation of the model, and in the study of the action of several factors, the inadequacy of the linear model can be explained by the appearance of significant coefficients of the products of the studied variables. The greater the curvature of the response surface, the more terms of higher powers are present in the regression equation, and the more coefficients have to be determined, resulting in a marked increase in the number of experimental variants.

The results of model experiments, in which the combined action of additions of metals on the phytoplankton and microzooplankton of the Bering Sea was studied, are given in Table 1. After the mathematical treatment, we calculated the regression equations which quantitatively describe the action of the studied additions of zinc and cadmium on the structural (numbers of microzooplankton) and functional (primary production) indices of the Bering Sea plankton communities. The calculated regression equations for the first experiment are

$$N_1 = 0.8 - 0.64x_2 - 0.2(3x_2^2 - 2) \quad (2)$$

$$N_2 = 1.3 - 0.33x_1 - 0.24x_2 + 0.21x_2^2 - 0.15x_1x_2^2 \quad (3)$$

$$N_3 = 0.44 - 0.60x_2 \quad (4)$$

$$P_g = 0.6 - 0.43_1 - 0.6x_2 + 0.71x_1x_2 \quad (5)$$

where N_1 is the total number of infusorians per thousand specimens in one liter,

N_2 is the total number of zooflagellates per million specimens in one liter,

N_3 is the total number of the dominant *Strombidium* infusorians per thousand specimens in one liter, and

P_g is the primary production of organic matter per mg C L^{-1} day^{-1}, and x_1 and x_2 are the additions of the metals cadmium and zinc, expressed in coded variables.

On the basis of the regression equations obtained, we plotted the response surfaces which graphically reflect the characteristics of the response of the selected indices to the action of pollutants (Figs. 1-5).

It is evident from Fig. 1 that the strongest inhibiting influence on the numbers of infusorians in the first experiments is exerted by additions of zinc in the first few days of the experiment. On the third day of the experiment, adaptive changes were noted in the community of infusorians that led to an attenuation of the toxic effect of metals (Fig. 1). However, on the fourth day of the experiment, the degree of inhibiting action of additions of zinc and combinations of cadmium and zinc increased again, although it was lower than one day after the addition of the metals to the experimental aquariums. It should be noted that 4 days after the start of the experiment, the addition of cadmium stimulated the development of infusorians. The combined action of the zinc and cadmium concentrations studied, one day after the start of the experiment, could be characterized as clearly defined synergism (Fig. 1). On the third day of the experiment, the synergism was observed only in the presence of additions of 0.5 mg/L of zinc and 0.05 mg/L of cadmium (Fig. 1). In all the other variants of the experiment, the combined action of zinc and cadmium was nearly additive. Thus, experiment I showed an attenuation of the degree of the inhibiting action of combinations of added metals on the numbers of infusorians. Apparently, this phenomenon resulted from succession changes of the initial infusorian community under action of the metals, and this was associated with a predominant development of the most stable forms of infusorians.

In contrast to experiment I, in experiment II, the greatest inhibiting action on infusorians was

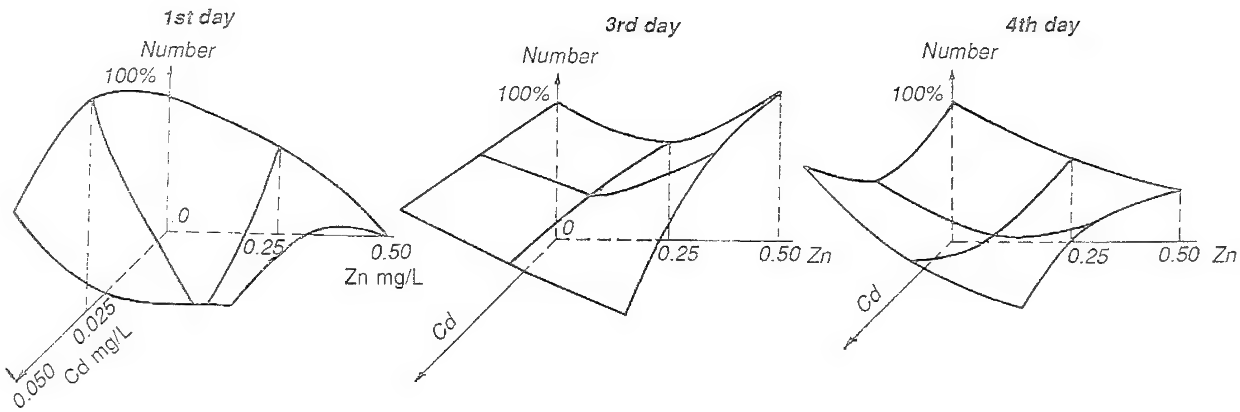

Fig. 1. Influence of additives of metals on the number of infusoria in experiment I in the Bering Sea (1981).

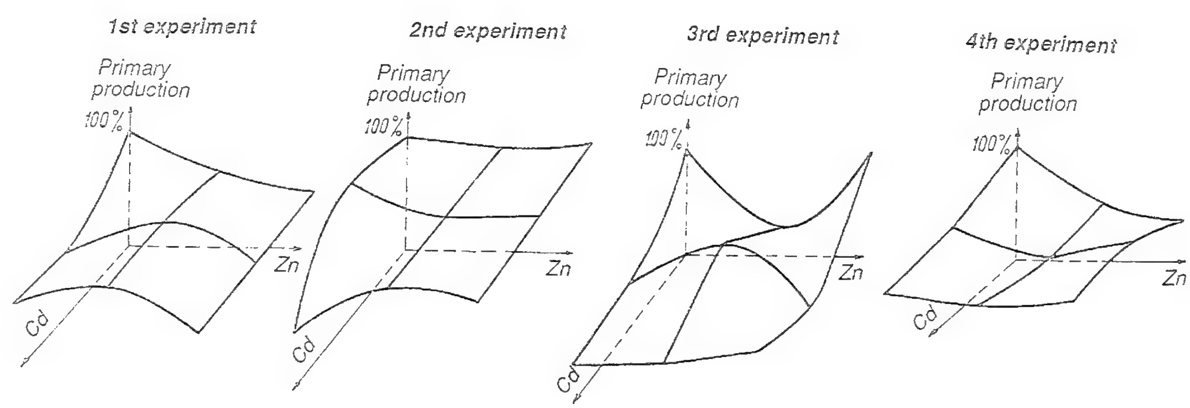

Fig. 2. Influence of Cd and Zn on primary production in the Bering Sea.

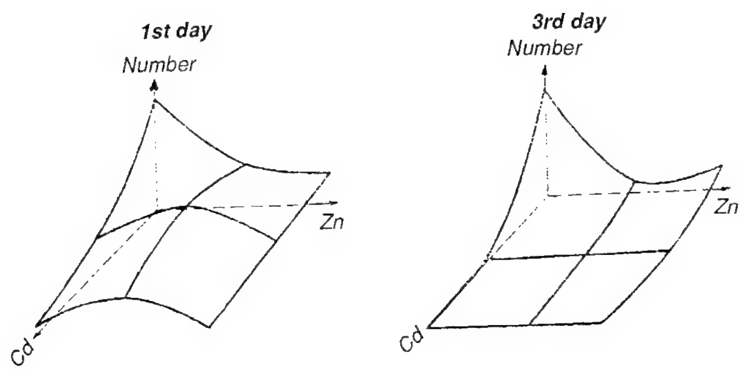

Fig. 3. Combined influence of additions of Cd and Zn on number of infusoria in experiment II in the Bering Sea.

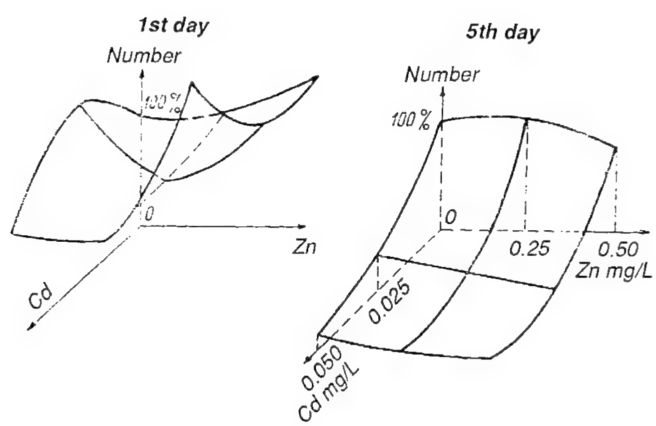

Fig. 4. Influence of Cd and Zn on the number of flagellates (experiment II).

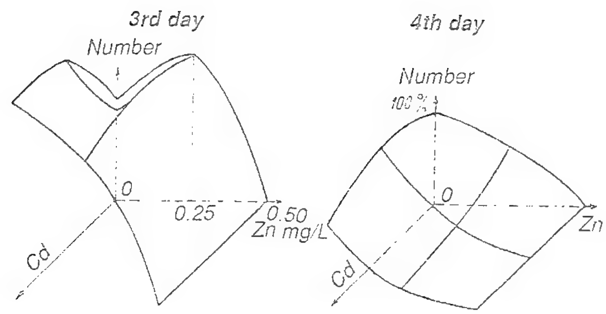

Fig. 5. Combined influence of Cd and Zn on the number of zooflagellates (experiment I).

exerted by additions of cadmium, and the negative action of both metals increased toward the end (Fig. 3). On the third day of the experiment, when the cadmium content of the water exceeded 0.025 mg/L, the numbers of infusorians decreased to zero. The combined action of the metals in the water was nearly additive for the entire experiment (Fig. 3).

The differences in the response of the infusorian community to the toxic action of cadmium in experiments I and II should be correlated primarily to the overall change in the ecological situation related to the seasonal succession changes of the plankton community. During the 1981-1984 study period in the northern polygon, a very rapid development of phytoplankton took place, and the abundance of zooplankton was relatively low, this being characteristic of the beginning of the period of biological spring. On the other hand, at the south and east deep-sea polygons, the rate of phytoplankton development decreased, but the quantity of organisms of mesozooplankton and microzooplankton increased, this being usual for the middle and end of biological spring.

The change in the general ecological situation was naturally accompanied by a change in the dominant forms of the organisms, including infusorians. As in the case of the north polygon, *Strombidium* infusorians predominated with numbers of 3.2 million organisms/m^3. At the south and east polygons, in the area of the continental slope, *Strombidium* dominated in the infusorian community, and *Tontonia tintinidae* were always present.

The first of the experiments discussed was conducted on 17 June 1981 in the area of St. Lawrence Island at station 13; the second, at station 30 on 26 June 1981 at the south polygon, the third, in 1984 at station 8 at the east polygon, and the fourth experiment was conducted at station 23 of the west polygon in 1984.

The experimental results, which represent the characteristics of the combined action of added zinc and cadmium on the magnitude of primary production and bacterial production, are shown in Table 3. Mathematical treatment of the data obtained showed the uncertainty of the effects of the studied metal concentrations on the magnitude of bacterial production, indicating a high stability of marine bacterioplankton to the added pollutants studied.

Figure 2 shows the response surfaces plotted on the basis of the mathematical treatment of the data of Table 2. It is evident from the figures that the most similar forms of the response surfaces were obtained in experiments I and IV. In these experiments, on the third day after the introduction of metals, both zinc and cadmium, acting separately, caused only a decrease in phytoplankton production, and the production values decreased steadily as the concentration of the metals increased. The nature of the combined action of metals in these experiments was essentially additive. When the content in the water was 0.25 mg/L for zinc and 0.025 mg/L for cadmium and 0.05 mg/L for cadmium, a certain attenuation of the combined inhibiting action of the metals took place (i.e., the phenomenon of ion antagonism was observed).

In the second experiment, the added zinc had practically no inhibiting effect on the primary production, and ion antagonism was also observed in the presence of cadmium additions (Fig. 2). The absence of a statistically reliable influence of zinc ions in this experiment can be explained, first, by the formation of organic complexes of zinc, with low toxicity to diatomaceous plankton, and second, by the difference in the individual sensitivity of the dominant forms of phytoplankton.

In the third experiment, carried out at the east polygon in 1984, in contrast to the previous ones, an anomalous stimulating action of 0.5 mg/L added zinc was observed (Fig. 2). The combined influence of the metals at medium addition levels or below was nearly antagonistic and at high addition levels exhibited a clearly synergistic character. It may be assumed that the characteristics of the response of the phytoplankton community in this area of the sea are due not only to a different species composition of the phytoplankton, but also to a different physiological activity of algae.

The similarity of the response of the phytoplankton community in experiments I and IV is due, in our view, to the fact that during both the former and latter experiments, an intensive bloom of diatomaceous algae was observed. It was shown earlier that the characteristics of the response of a phytoplankton community depend to a large extent on the physiological activity of algae, the pollutants being most toxic at the very beginning of the bloom (Filenko and Khobotyev 1976; Patin 1979).

Despite a certain difference in the response of the investigated phytoplankton communities to the added metals studied, the following general features can be identified on the basis of an analysis of the data obtained: (1) in the range of studied concentrations, from background ones to 0.5 mg/L for zinc and 0.05 mg/L for cadmium, added cadmium had a considerably stronger inhibiting effect; (2) the combined action of the metals, in the presence of their content in the water no higher than the average level of the added metals, was additive or antagonistic; (3) in the range of both concentrations of the two metals studied, in excess of the average level, the antagonism and additivity were usually replaced by synergism (i.e., a reinforcement of the combined action of the metals took place).

In experiments aimed at studying the action of BP and PCB on microzooplankton, it was found that infusorians are particularly sensitive to these pollutants, since their quantity dropped sharply only one day after the introduction of the pollutants. The most inhibiting action on flagellates resulted from additions of benzo[a]pyrene (BP) (Table 3).

Thus, the analysis of the data obtained shows a pronounced toxic effect of the studied concentrations of zinc and cadmium and chlorinated and polycyclic aromatic hydrocarbons on the phytoplankton and microzooplankton. The high sensitivity and reactivity of the microzooplankton organisms permit their future use in an ecological monitoring system as biological indicators of the status of the marine environment.

Table 3. *Combined influence of additions of benzo(a)pyrene (BP) and polychlorinated biphenyls (PCB) on the number of infusoria (N_1 in thousands of specimens/L), zooflagellate (N_2 in millions of specimens/L) and phytoflagellate (N_3 in millions of specimens/L) in experiments conducted in the Bering Sea.*

Experiment No.	Diagram of additives		1st experiment	2nd experiment					1st experiment	
Variable no.	BP (μg/L)	PCB (μg/L)	3rd day	1st day			3rd day		1st day	
			N_1	N_1	N_2	N_3	N_2	N_3	N_2	N_3
1	trace	trace	0.82	2.60	0.28	0.64	0.22	0.84	0.05	0.09
2	5	trace	0.09	0.08	0.17	0.10	0.28	0.28	2.2	0.12
3	0	trace	0.07	0	0.16	0.05	0.50	0.12	0.8	0.02
4	trace	15	0.15	0.24	0.21	0.45	0.91	0.76	0.4	0.07
5	5	15	0.24	0.60	0.07	0.02	1.2	0.22	0.3	0.03
6	0	15	0.005	0	0.05	0.02	0.82	0	0.09	0
7	trace	30	0.02	0.64	0.21	0.43	1.9	0.70	0.05	0.02
8	5	30	0.03	0	0.05	0.02	0.53	0.02	0	0.02
9	0	30	0.05	0	0.03	0.02	0.33	0	0	0.02

Added benzo[a]pyrene had the most toxic effect on the abundance of the zooflagellates. In the majority of the experiments, the numbers of infusorians in the presence of BP and polychlorinated biphenyls dropped sharply, indicating a particular sensitivity of this group of organisms to the hydrocarbons studied. Among the metals studied, the most toxic in the range of the concentrations studied was found to be added zinc. The inhibiting effect of added cadmium was much less apparent.

The data of experiments carried out under nearly natural conditions in the Bering Sea indicate a pronounced toxic effect of heavy metals and chlorinated and aromatic hydrocarbons at concentrations tens and hundreds of times greater than those existing at the present time. The investigation established the presence of an interaction between the studied pollutants, which led to a reinforcement of the combined negative influence of the pollutants; this proves the validity and necessity of an experimental study of the characteristics of the combined action of different pollutants on natural plankton communities.

The appreciable differences noted during the study in the response of plankton communities from different areas of the Bering Sea to the action of the toxicants studied calls for future use of a regional approach to the selection and experimental determination of the critical concentrations of pollutants, necessary for estimating the assimilation capacity of ecosystems in different geographic zones.

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SOME ASPECTS OF THE RESPONSE OF PELAGIC INFUSORIANS OF DIFFERENT ZONES OF THE BERING SEA TO TOXIC ACTION

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It is impossible to make specific recommendations with regard to organizing an efficient system of ecological monitoring of the state of the ocean without studying the most important properties of pelagic communities (Shmal'gayzen 1963; Odum 1975). Such properties, which are the ones most responsible for determining the nature of the monitoring, include sensitivity (a property determining the maximum allowable anthropogenic load on the water area being monitored), stability (this property of communities is directly related to the space-time regime of ecological monitoring), and finally, potential vulnerability, a concept that makes it possible to predict the aftereffects of the action of pollutants on the communities (Lifshitz 1977; Zelikman 1977; Maksimov et al. 1988).

Using the example of a community of pelagic infusorians, researchers noted that an important group of microzooplankton demonstrates certain possibilities of the experimental approach to the study of these characteristics, which are important in monitoring practice (Stepanova 1937; Shmal'gayzen 1963; Tymantseva and Sorokin 1975; Burkovskiy 1976; Lifshitz 1977; Zelikman 1977; Tymantseva 1978; 1980; Stepanov 1983; Mamaeva 1987).

In an experimental study of the reactions of a community of pelagic infusorians to toxic influences, we have tried to get an answer to two basic questions: Do the reactions differ between protozoans from qualitatively different areas of the Bering Sea? Does the pollution regime (residence time in a medium with a high content of pollutants) exert an appreciable influence on the degree of response? To answer these questions, we set up four experimental runs. Three runs were set up according to the complete factorial experiment (CFE) scheme. We used the CFE 3^2 scheme (Korsak 1976; Nikiforova and Korsak 1978; Nosov et al. 1981; Maksimov et al. 1988). The toxicants used were copper and cadmium, which in individual variants were added as shown in Table 1. The CFE 3^2 experiments were conducted at the central stations of south, east, and north polygons. The waters of the south polygon are formed largely under the influence of the Alaska and East Bering Sea Currents; the east polygon is a typical halistatic area. The water mass to which the north polygon is confined is highly dependent on the Arctic Ocean waters penetrating here (Stepanov 1983). This area is marked by a generally elevated dynamism. All

Table 1. *Diagram of toxicant additives of CFE 3^2. (-=0 mg/L; 0=0.025 mg/L; and +=0.050 mg/L).*

Experiment no.	Cd	Cu
1	-	-
2	0	-
3	+	-
4	-	0
5	0	0
6	+	0
7	-	+
8	0	+
9	+	+

the experiments were conducted in 15-L aquariums. The water was sampled from the surface with a plastic bottle. Each of the three runs lasted three days. Every day, 10-mL samples were taken, and a Bogorov chamber was used to do the total count of bare infusorians and also to estimate the relationship of nine of the most typical protozoan morphotypes in the community. The 3-day period of the experiments was due to the fact that during that period, the trend of the response in the control aquarium was insignificant. Then the flask effect increases, and further conduct of the experiment ceases to give reliable results.

The fourth run was conducted at the north polygon. The 3-day experiment (Table 2) was set up in aquariums to which nutrients were added. Every day, water was taken from the aquariums in 27 production flasks (3 from each aquarium). Nine flasks received 0.025 mg/L of copper, another nine, 0.025 mg/L of cadmium, and another nine, 0.025 mg/L of lead. The addition of nutrients did not have a distinct negative effect on the community, but stimulated a change in its structure. The fourth experimental run should have answered the question concerning the nature of the influence of the toxicants at different stages of the rearrangement of the species structure of the community.

In estimating the impacts on the community by the toxicants, what is important is not the absolute change in the numbers of the protozoans, but the degree of transformation of the structure of the community. The toxic effects are of such intensity that they are capable of deforming the community significantly, that is, from a general ecological point of view they should be considered critical (Odum 1975; Lifshitz and Korsak 1987).

We had shown earlier that the critical concentrations can be identified without performing a direct analysis of the structure of the community (this is an extremely cumbersome process, and in the case of a group with an unstudied taxonomy, which includes pelagic infusorians, generally difficult). Our methodology, which is somewhat similar to the tenets of the catastrophe theory (Arnold 1985), is based on a geometrical analysis of the shape of the surfaces of the responses of synecological indices to toxic action. In this case, we refer as synecological to indices whose magnitude depends in some measure on all the species comprising the community (Odum 1975). Combinations of toxicant concentrations causing the transformation of a species structure simultaneously initiate the formation, on the response surface, of local extreme which disturbs the integrity of the surface. By identifying such local extreme, we thereby also identify combinations of critical concentrations. To detect local extreme, it is convenient to use the following rule: The integrity of the surface breaks down when the response to a weaker action proves stronger than the response to a stronger action. Of two combinations of toxicants, a stronger action is exerted by that combination in which at least one ingredient is present in a large amount. It is understood that any pair of variants can be ranked according to the strength of action of the corresponding combinations of toxicant concentrations. In our case, the ratios of the strength of action in individual variants are listed in Table 3.

Table 2. *Diagram of biogenic additives of CFE (fourth series). (- = 0 μm/L; 0 $N \cdot NO_3$ = 5μm/L; 0 $P \cdot PO_4$ = 0·6 μm/L; + $N \cdot NO_3$ = 25 μm/L; + $P \cdot PO_4$ = 3μm/L.)*

Experiment no.	$N \cdot NO_3$	$P \cdot PO_4$
1	-	-
2	0	-
3	+	-
4	-	0
5	0	0
6	+	0
7	-	+
8	0	+
9	+	+

The number of local extremes uncovered in comparing the reactions of a community in this manner is a good measure of the ecological depth of the aftereffects of the action of toxicants, and the set of combinations of concentrations initiating the formation of local extreme determines the limits of critical actions.

Tables 4 and 5 show the results obtained for the number of local extreme on different response surfaces. Figures 1 and 2 show the corresponding response surfaces. The number of infusorians in the surface waters of the stations at which the experiments were conducted was 1,000-10,000 organisms/L, which is typical of the Bering Sea during the spring-summer period. In all cases, the number of protozoans in the control was taken to be unity.

In analyzing the results obtained, attention is drawn first to the increase in the negative aftereffects of the action of toxicants. Table 1 indicates that adaptation to the actions as the exposure time increases is not observed in any of the cases. In this sense, the experimental results confirm the statement that despite the increasing anthropogenic pressure on the Bering Sea, this body of water can still be counted among the background ones. In any case, the community of pelagic infusorians is not adapted to the action of xenobiotics. It is also important to note that the long periodicity of the pollutants is no less dangerous than a direct increase in pollutant concentration. An increase in exposure time leads to aftereffects no less harmful than a direct increase in concentrations. In light of this, the prospect of oil production in this region is attracting particular attention. Experiments show that despite preventive technological measures, petroleum industries very quickly become sources of chronic pollution.

Table 3. *Relative strength of the effect of combinations of toxicant concentrations in different variants of CFE 3^2.*

Variant no.	Variant no., in which the effect is weaker
1	-
2	1
3	1; 2
4	1
5	1; 2; 4
6	1; 2; 3; 4; 5
7	1; 4
8	1; 2; 4; 5; 7
9	1; 2; 3; 4; 5; 6; 7; 8

While the general trend toward an intensification of the response is manifested quite clearly in all cases as the anthropogenic pressure increases, the nature of this process is different in different areas of the Bering Sea. The most profound changes in the action of copper and cadmium take place in the halistatic zone, and the smallest changes take place in the frontal regions. This is due to the high dynamism of the environmental parameters of infusorians in the frontal zones. The community adapted to these fluctuations and acquired additional reserves to offset the negative effects. Of interest is the fact that a more labile community tolerates unfamiliar loads more easily, and in the case under consideration, it is the toxicant concentration, unusually high for the Bering Sea.

It is interesting to note that plane geometry permits a more accurate assessment of the dynamism of ecological conditions. Thus, the northern areas are more dynamic than the southern ones. The number of local extreme on the response surfaces obtained in the south is also somewhat greater. The statement that there is a relationship between the extent of the reaction of the protozoan community to the dynamism of the environment also finds confirmation in the results of the direct experiment (fourth series). Additions of nutrients do not have any distinct negative influence on protozoans, but stimulate profound rearrangements of the latter (probably by acting on infusorians

Table 4. *Number of local extremes, which appeared on surfaces of CFE responses 3^2 (1-3 series).*

Time of exposure	Polygons		
	South	East	North
1st Day	3	7	0
2nd Day	2	9	2
3rd Day	7	11	4

Table 5. *Number of local extremes, which appeared on the surfaces of CFE responses 3^2 of the fourth series.*

Time of exposure	Biogenic and toxicant additives			
	N + P	N + P + Cu	N + P + Cd	N + P + Pf
1st Day	9	8	21	18
2nd Day	6	17	3	4
3rd Day	16	0	3	2

indirectly via the phytoplankton). When the rearrangements of the protozoan community are particularly rapid (third day of the experiment), the action of metals has the smallest effect.

In analyzing the character of the individual surfaces, one can see a high toxicity of those combinations of pollutants in which copper is present. Copper is one of the leading toxicants. Apparently this result, obtained in the course of physiological toxicological experiments, also remains significant in estimating the ecological aftereffects of pollution of the marine environment. In discussing the results of individual experiments, the following effect should be noted: If the action of toxicants gives rise to a local extremum on the response surface, this extremum usually does not disappear as the exposure time increases (obviously, if there is no temporal adaptation of the community). Short-term experiments probably make it possible to obtain more significant results characterizing the reaction of the community to toxic actions, results not limited by the time of the experiment. The identified trends can be carefully extrapolated.

The characteristics of the change in the values of the synecological characteristic are closely related to the transformation of the structure of the community under the influence of the toxicants. In our case, three basic trends in the change of the morphotype ratio were recorded. When the toxic action is weak, no disturbance of the proportions of the individual morphotypes comprising the community of pelagic infusorians is observed. This is the region of so-called nonspecific reactions of the community. At this stage, the relationships existing between individual groups of infusorians are not disturbed. The concentrations initiating nonspecific reactions can be classified as subcritical. A subsequent increase of the content of metals in the medium (or an increase in exposure time) usually leads to a leveling of the size structure of the community. Different morphotypes become represented to approximately the same extent. Concentrations causing such

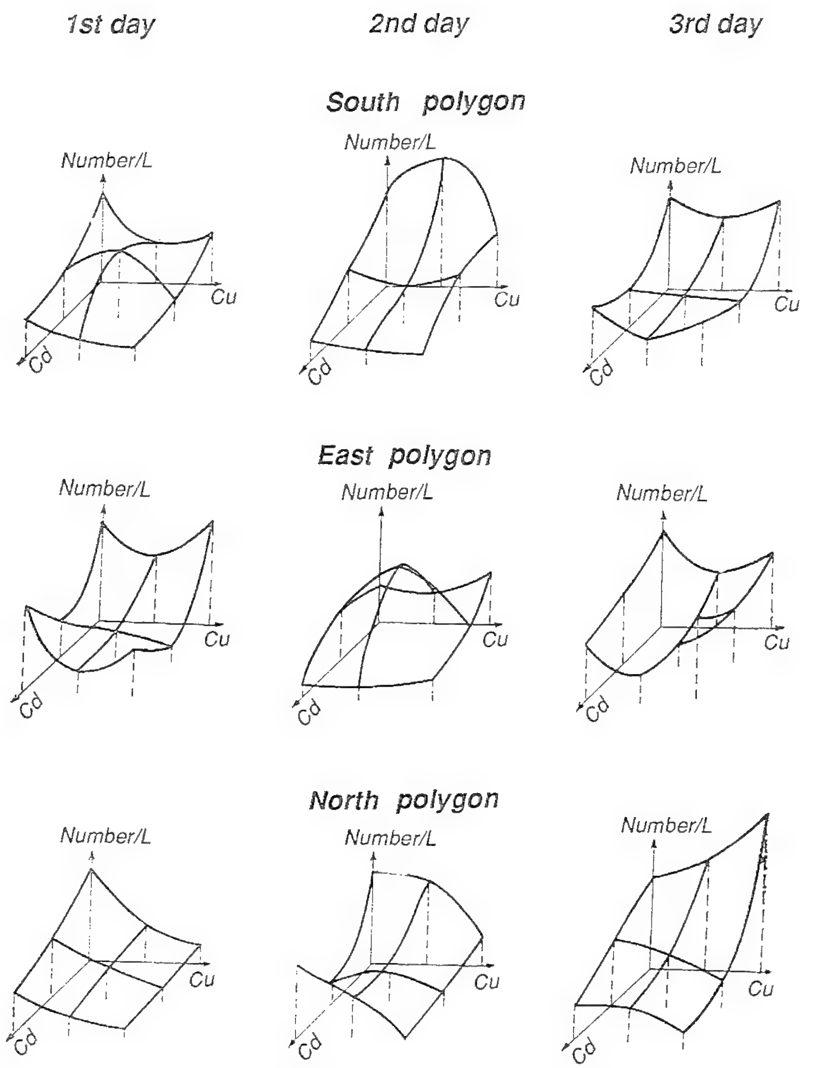

Fig. 1. Surface responses in CFE 3^2, 1-3 Series.

an effect (specific reactions of the community) can be classified as critical. At this state, local extremes appear most frequently, and additional actions cause the strongest responses. We often also encounter the aftereffects of supercritical actions. The size structure of the community is already highly transformed in this case. Infusorians of round shape began to predominate (i.e., a trend toward minimization of the total surface of the cells comprising the community is seen). This is natural when the toxicity of the medium is high.

The work makes it possible to draw the following conclusions:

1. Factorial experiments are a fairly convenient means of estimating the degree of action of toxicants on natural communities. Using the results of CFE 3^2 geometry methods in the analysis makes it possible to obtain very significant results pertaining to the ecological after effects of an increase in anthropogenic pressure.

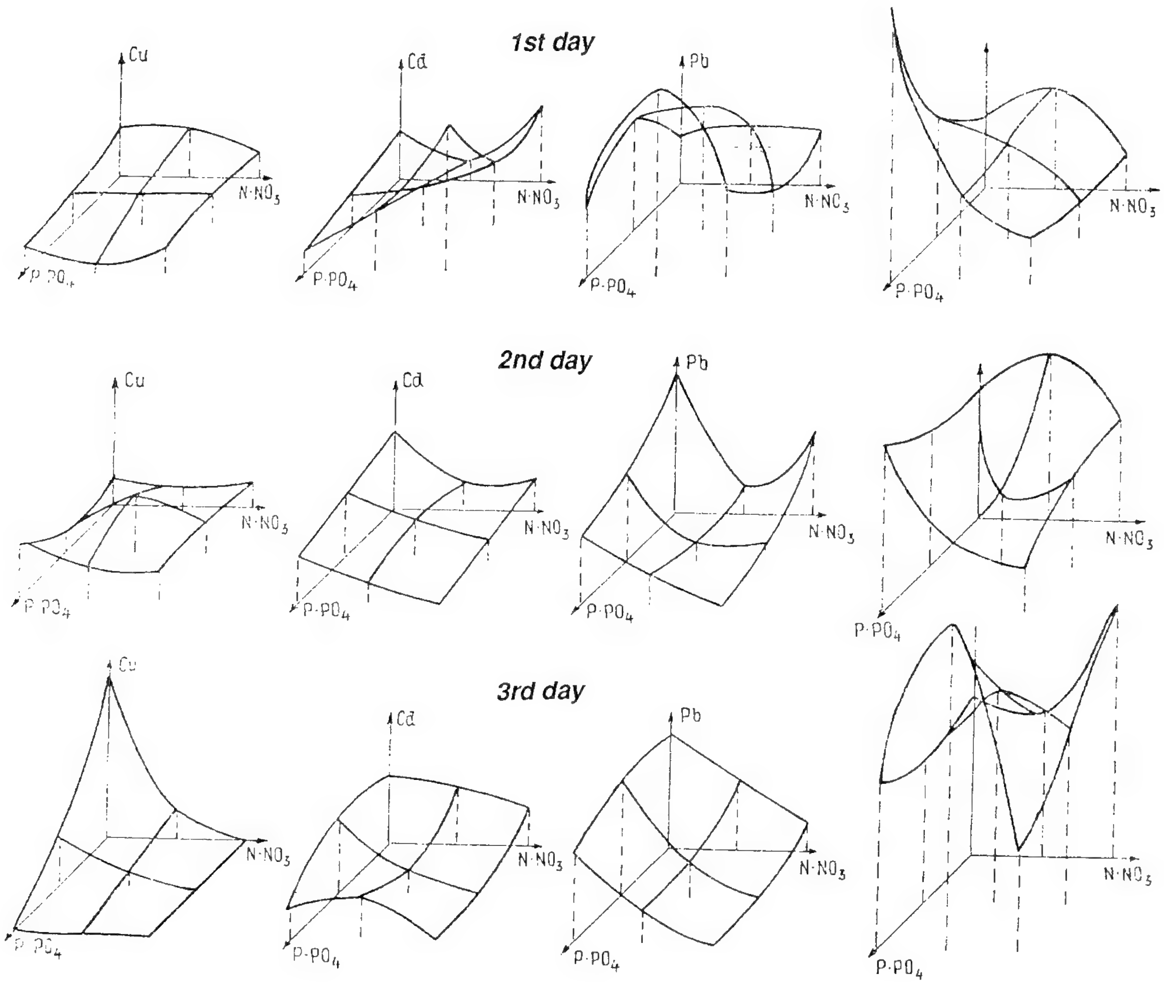

Fig. 2. Surface responses in fourth series of CFE 3^2 + (Cu:Cd:Pb).

2. The community of pelagic infusorians of the Bering Sea is not adapted and very vulnerable to the action of heavy metals. This applies particularly to the simplest stable areas. The economic development of the Bering Sea region should be approached very carefully.

3. The size structure of the community changes regularly as the toxicity of the environment increases. In the presence of subcritical actions, the ratio of the size groups remains unchanged. Then the leveling of the size structure becomes fixed. Finally, we encounter the phenomenon of minimization of the total cell surface.

4. The conduct of standard short-term factorial experiments creates the fundamental premises for obtaining an effective ecological-toxicological indication of the status of pelagic communities and of the stability of their environment.

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THE EFFECTS OF TOXICANTS AND NUTRIENTS ON PLANKTON BIOMASS AND DYNAMICS IN THE BERING SEA

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Introduction

The reaction of a natural plankton community to toxic influences depends upon the concentration of toxicants and the ecological resistance of the community (ecological protection tolerance). Ecological resistance of a community to inhibitive substances depends not only on species composition, but also on its total physiological state, which is determined by the level of ecological diversity. Integration of physiological and ecological characteristics determines whether a community can decrease toxic influences by using protectional physiological and ecological adaptation mechanisms (e.g., changing species composition). The purpose of this investigation was to study the ecological resistance of the natural phytoplankton and microzooplankton communities in different regions of the Bering Sea. The short ecological-toxicological experiments were carried out during a joint U.S.-U.S.S.R. expedition to the Bering Sea in 1984. The station locations ranged from the deep Bering Sea in the south polygon through the shelf break ecosystem at the east polygon to the north Bering Sea Continental Shelf in the north polygon (frontispiece).

Methods

The experiments were carried out using a "dose-effect" scheme at different stations of a north-south transect. The samples of seawater used in the experiments were taken from 0.5-, 10-, 15-, and 25-m depths, and the experiments with model plankton ecosystems were performed on board the RV *Akademik Korolev*. Each sample was split into five subsamples for additions of 0, 1, 5, 10, and 50 μg copper/L. The subsamples were incubated in a natural-light bath with running seawater for 24 h, after which the primary production of phytoplankton and the total number of infusoria were determined. The infusoria in unpreserved samples were counted in a 10-mL Bogorov chamber, by using a binocular microscope. The primary production rates were determined by using the ^{14}C method. Radioactivity of the solutions and filters were measured by using a Mark-2 Nuclear Chicago scintillation counter and the scintillation cocktail (Korsak 1987).

As a result of our experiments, we obtained data (Table 1) on the influence of Cu concentrations on the total number of infusoria and the rate of primary production. These data were used to calculate LD-50 and LD-90

response parameters of various plankton communities in different regions of the Bering Sea (Lifshitz and Korsak, in press).

Results

Before a detailed description of the changes in LD-50 and LD-90 experiments for phytoplankton and microzooplankton, the main oceanographic and ecological features of the investigated areas in the Bering Sea will be described.

The largest biomass of infusoria lives in the upper 45 m of the water column, which includes the euphotic zone in the Bering Sea (Fig. 1). At depths greater than 70 m, there were small numbers of infusoria. The vertical distribution of the total number of infusoria was very different in the southern and northern regions of a transect running from station 3 to station 14. At the southern stations of the south-north section, the maximum number of infusoria was observed in the depth range of 10-15 m (Fig. 1). The mean value of total number of infusoria in the middle of the transect (stations 5-9) was approximately 2 x 10^6 organisms/m^3. The total number of infusoria decreased at stations 9, 10, and 11 compared to the southern region but increased again at the northern stations (12-13). The maximum total number of infusoria were counted at station 13 (2.2 x 10^6 organisms/m^3).

The Soviet and American primary production data obtained by different modifications of the ^{14}C method both showed a significant trend to increasing primary production from south to north (Whitledge et al., in press; Korsak and Nikulin, in press). The highest values of primary production were measured near St. Lawrence Island at stations 13 and 14. There were similar changes of integrated chlorophyll *a* and nutrient content in the upper 40-m layer (Fig. 2). The concentrations of N, P, Si, and chlorophyll *a* were more than two times as large in the 40-m layer at stations 13 and 14 than at other sampling sites. During the Soviet expedition on the RV *Akademik Shirshov* in 1981, the largest value of primary production (1.4-3.8 g C m^{-2} day^{-1}) was measured at stations of the north polygon near St. Lawrence Island (Tsyban and Korsak 1987). Very significant variations in the value of primary production were also observed between stations

Table 1. *The effects of different concentrations of copper on the primary production, compared to controls (all controls = 100) in "dose-effect" experiments.*

Depth	Cu Concentrations (µg/L) 1	5	10	50
Station 14				
0	67	77	43	25
10	71	44	28	20
15	65	22	27	17
25	65	61	21	31
Station 17				
0	54	40	41	41
10	78	72	79	77
15	61	72	46	43
25	56	50	38	40
Station 12				
0	68	52	41	46
10	91	30	31	22
15	50	91	20	15
25	81	31	25	23
Station 11				
0	81	41	30	35
10	70	48	38	43
15	70	50	42	49
25	109	84	88	64
Station 10				
0	54	30	24	19
10	63	51	39	32
15	68	39	41	27
25	46	44	20	14

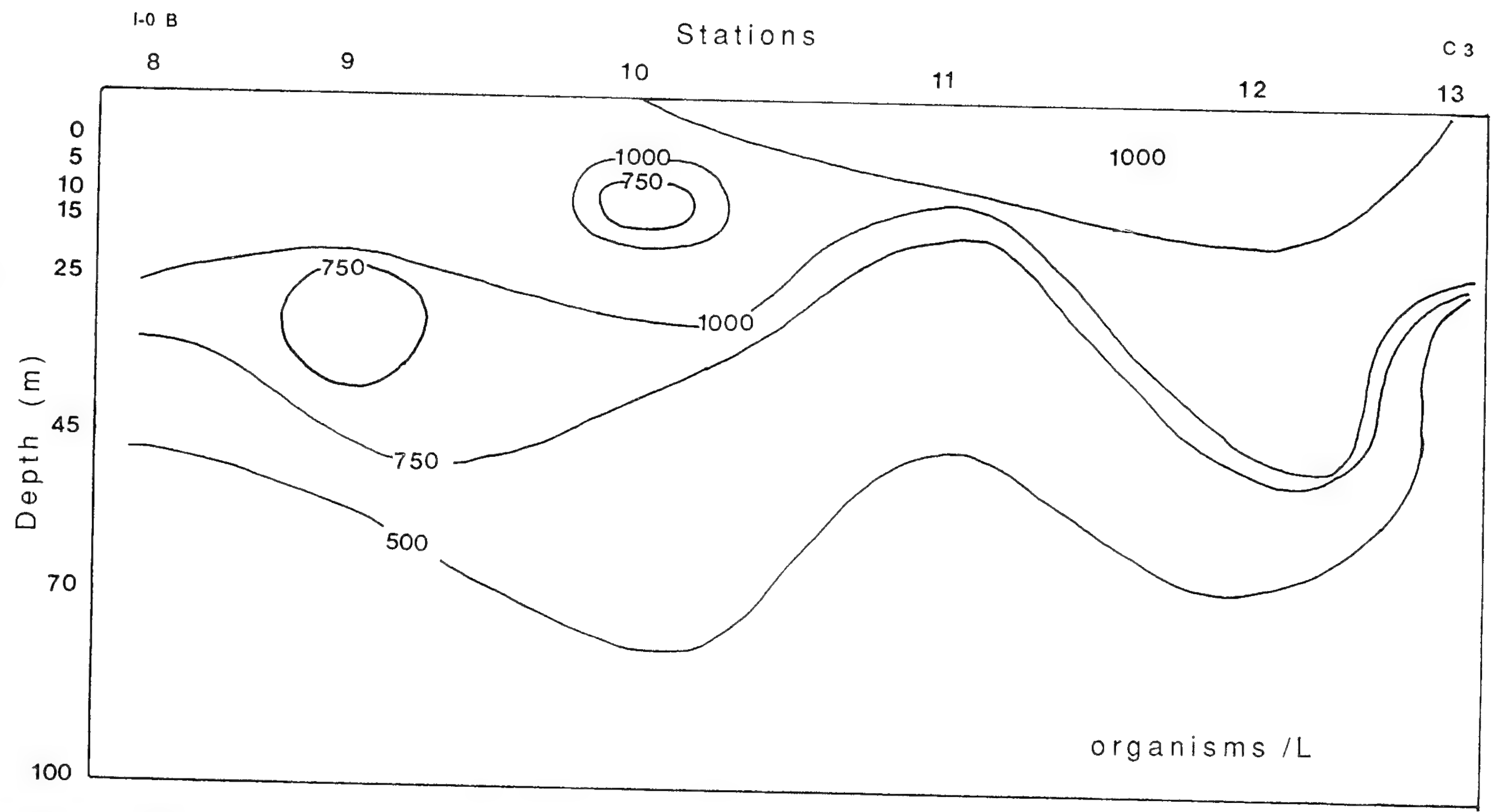


Fig. 1. The vertical distribution of total number of infusoria.

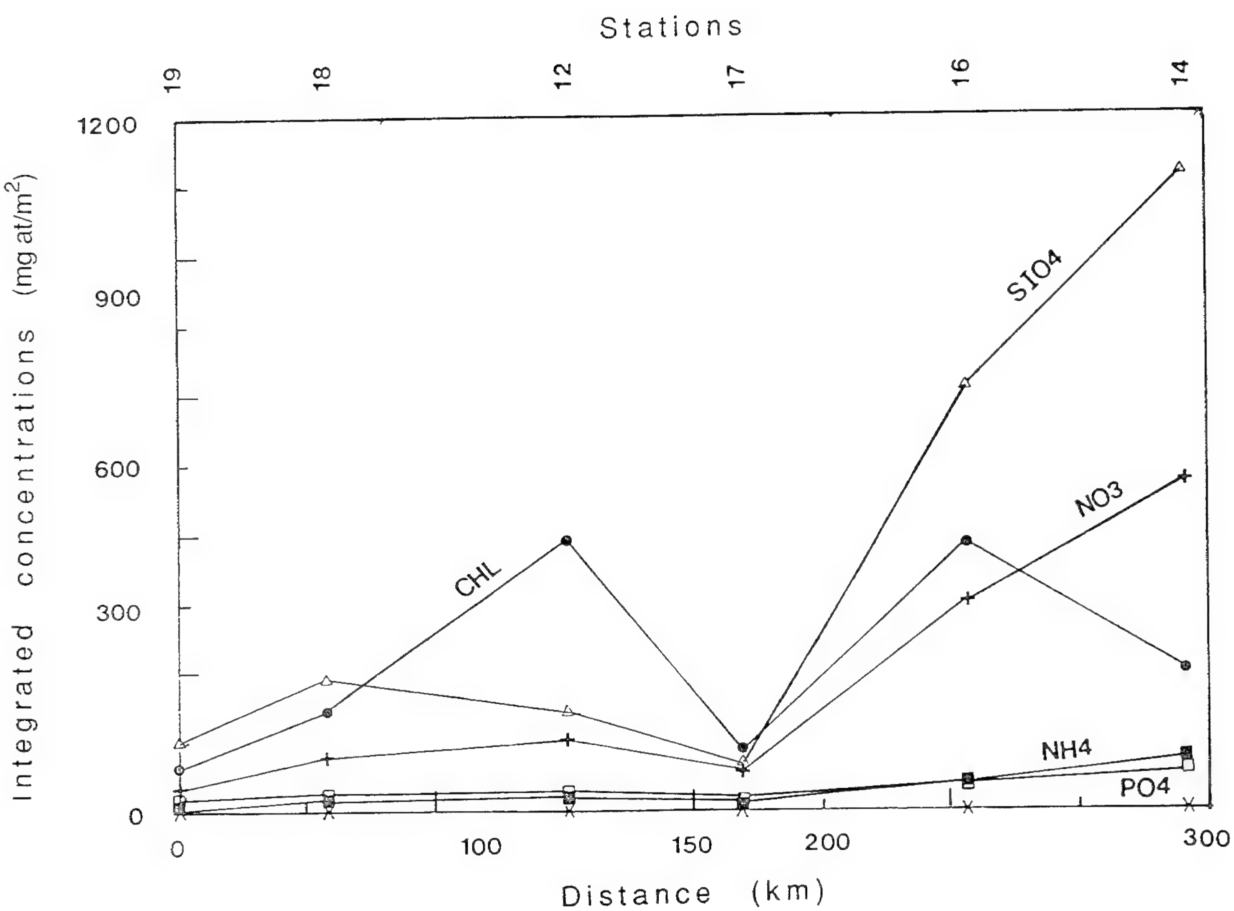


Fig. 2. The vertically integrated concentrations of biogenic nutrients and chlorophyll *a* over the upper 40-m layer near St. Lawrence Island.

of the north polygon. All biological and hydrochemical data obtained during the joint expedition showed that the area near St. Lawrence Island was highly productive, and we studied an intensive spring diatom bloom during our investigation. All these results indicate the existence of bathymetrically induced upwelling at stations in the area of St. Lawrence Island (Whitledge et al. 1988).

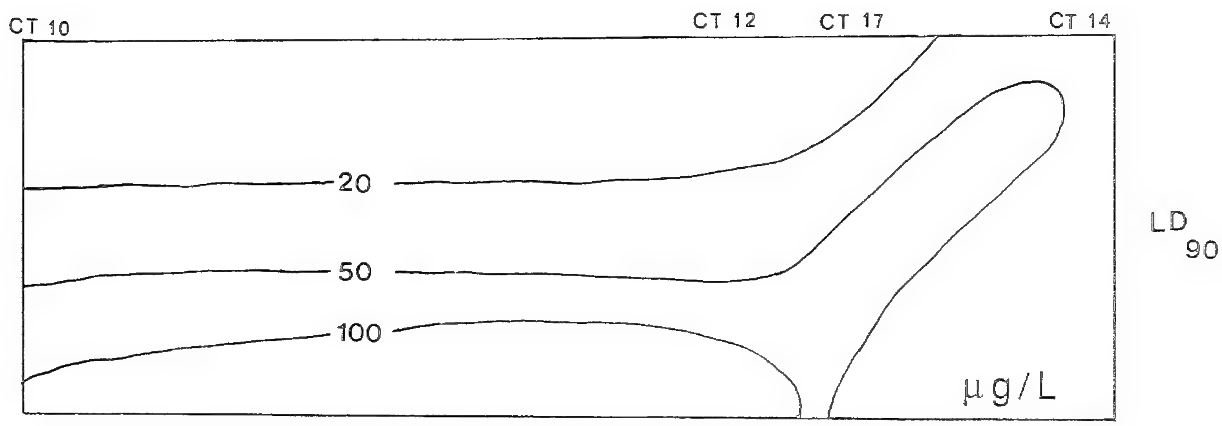
The data of different pigment concentrations and species composition help us to understand detailed changes of the phytoplankton communities along the north-south transect that encompasses the deep Bering Sea, the shelf break, and the Continental Shelf ecosystems.

Near St. Lawrence Island, there was an intensive diatom bloom (Senitckina and Wentzel, in press), especially *Thalassiosira nordenskioldii* and *Chaetoceros socialis*, which are common in a spring phytoplankton community that develops in a high concentration of nutrients. These data correlate well with phytoplankton pigment concentrations of chlorophyll *a* and fucoxanthin and show the possibility and importance of using pigment composition as a "diagnostic marker." South of station 17 was another phytoplankton community, which is more common for the summer period in the Bering Sea (Whitledge et al., in press). The main feature of this community was domination by diatoms, especially *C. compressus, C. concavicornis, Leptocylindrus danicus*, small numbers of *Peridinium* algae, and *Prasinophycea* algae (genus *Halosphaera*) at stations 5, 6, and 9 (Senitckina and Wentzel, in press). At stations 5 and 6, this species of algae represented a significant biomass because the size of the individual cells varied from 30 to 400 μm. It should be mentioned that the chlorophytes that contain chlorophyll *b* were observed in a narrow layer of the euphotic zone of depths between 20 and 30 m.

The value of LD-50 and 90 of Cu (Fig. 3) for primary production increases from 0.5 to 25 m for all stations investigated. The changes of LD-50 and especially LD-90 exhibit regularity, and on stations 10 to 12, the LD isolines are located at an approximately constant depth. A similar trend of the LD-50 and 90 for Cu occurs for microzooplankton in the south and central regions (stations 3-12), but after station 12, primary production and the LD-50 and 90 isopleths rise to the surface layers.

There is a significant difference in the values of LD-50 and 90 between the surface and the 25-m depth for primary production and microplankton (Figs. 3 and 4). The values of LD-50 and 90 for primary production increase from the surface to deeper layers and vice-versa for microzooplankton (Fig. 4). We cannot clearly explain why the phytoplankton and microzooplankton exhibit these opposing trends without further experiments. But we can propose that the trends may be explained by inverse correlation between phytoplankton and microzooplankton, as determined by their food-chain dependence and the role of bacteria as an intermediate element between the two groups. In spite of such different reactions for primary production and microzooplankton at different depths, the dynamics of the LD-50 and 90 parameter allow us to separate two regions along the S-N transect.

In the south and central stations of the transect, the reactions of phytoplankton and microzooplankton communities at each station were not very different. In the north region near St. Lawrence Island (stations 12-14), considerable differences of Cu toxicity to phytoplankton and microplankton were observed at different depths. The surface communities of phytoplankton and microzooplankton near St. Lawrence Island were more tolerant of toxic concentrations of Cu than the same communities located south of station 12. As it was described earlier, all biological and oceanographic parameters, including nutrients, were very different in these two regions, as shown by ecological-toxicological profiles of LD-50 and 90 of plankton characteristics (primary production and the number of infusoria).



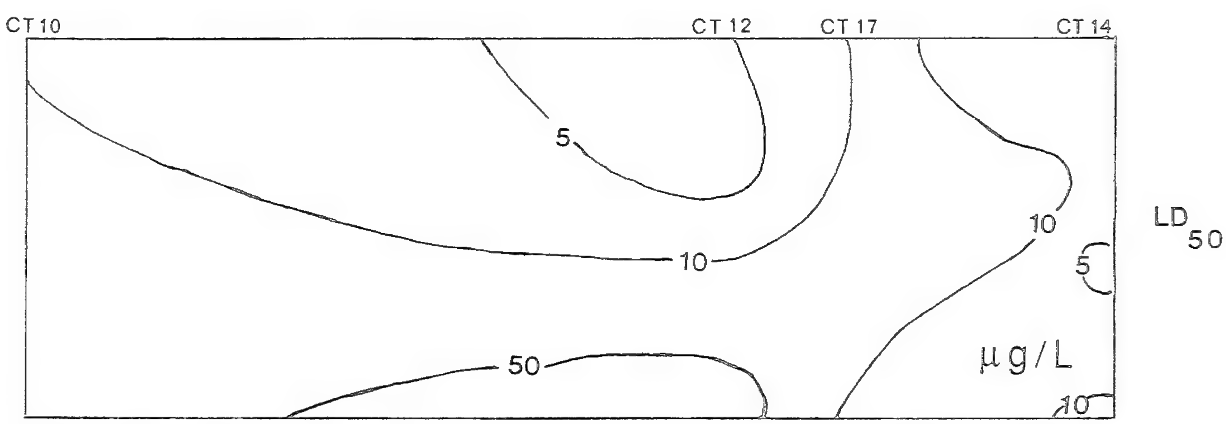


Fig. 3. The vertical distribution of LD-50 and LD-90 isopleths for primary production.

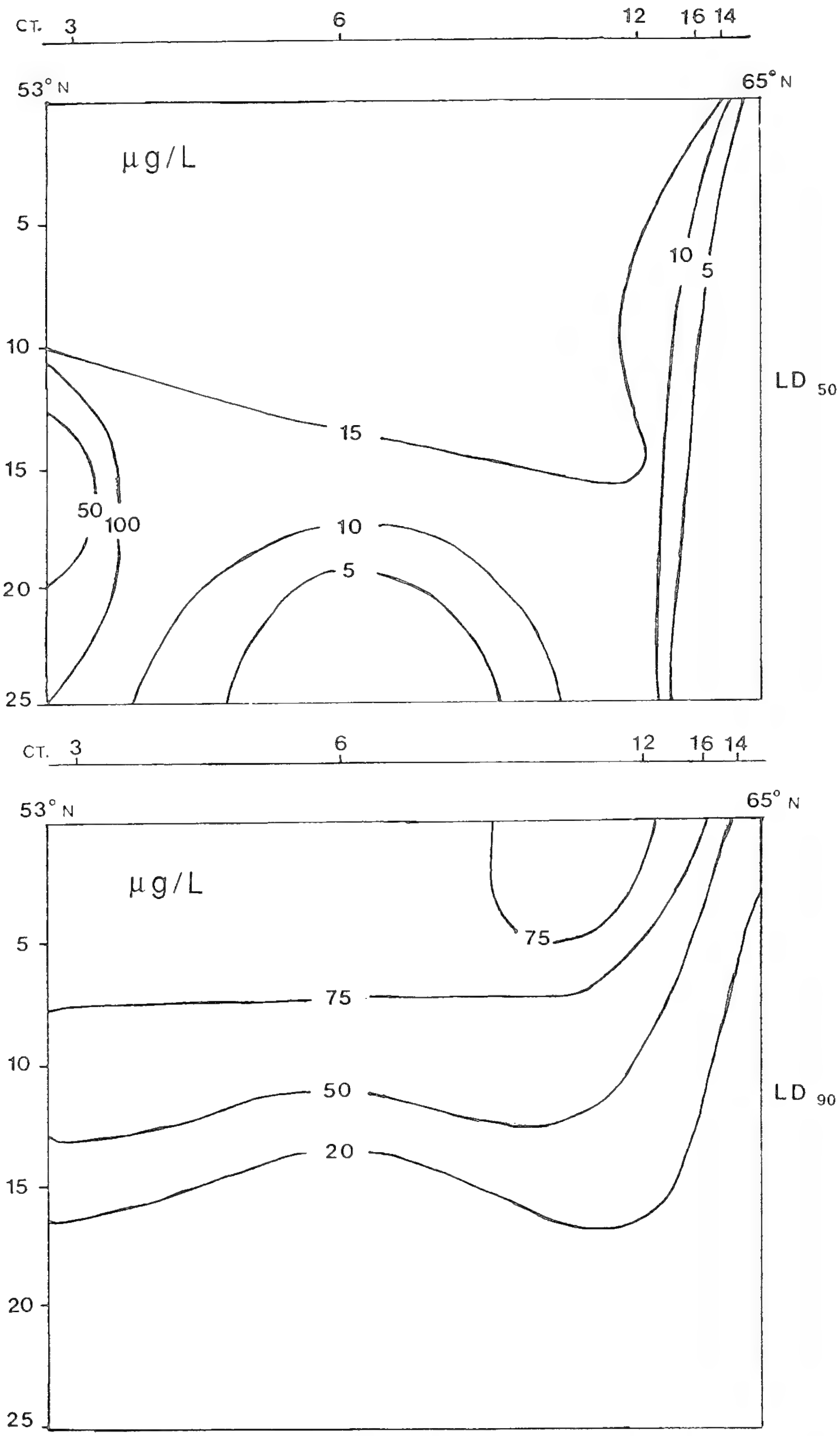


Fig. 4. The vertical distribution of LD-50 and LD-90 isopleths for total number of infusoria.

So by using the scheme of dose-effect experiments with toxicants for studying the reaction of plankton communities at different depths, we can measure not only LD-50 and 90 variations, but also test the ecological-protection tolerance of the natural plankton communities in different study areas. Last, it should be mentioned that LD-50 and 90 variations for primary production and the number of infusoria show us the approximate value of critical concentrations for Cu in the Bering Sea ecosystem. The mean values of LD-50 of Cu for primary production in the central regions of the Bering Sea during the period of investigation were 4-7 μg Cu/L. Because some areas of the Bering Sea ecosystem have concentrations of Cu that are nearly 1-2 μg/L (Heggie 1982), we believe that if Cu concentrations in the euphotic zone increased by 2-3 times, there would probably be significant, negative ecological consequences that could disturb the balance of the normal plankton community.

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Protocol

Protocol

II-nd Soviet-American Expedition in the Bering Sea

(27 June - 31 July 1984, R/V *Akademik Korolev*)

In accordance with the plans of the American-Soviet cooperation in environmental protection (the bilateral agreement of 1972) under the Project 02.05-41 "Biosphere Reserves" (subtheme: Bering Sea Ecosystem Studies) and the meeting of American and Soviet specialists (Moscow - Tallin, 4-11 March 1984) the Second Joint American-Soviet Expedition to the Bering Sea was held on 27 June - 31 July 1984 on board the Soviet research vessel *Akademik Korolev*.

The Soviet institutions that participated were: Natural Environment and Climate Monitoring Laboratory, Goskomgidromet and USSR Academy of Sciences, Institute of the Biology of South Seas of the Academy of Sciences of the Ukrainian SSR, Odessa Branch; Institute of Biology of South Seas of the Academy of Sciences of the Ukrainian SSR, Sevastopol; Far East Regional Research Institute of Goskomgidromet.

The American institutions that participated were: U.S. Fish and Wildlife Service, Department of the Interior; Harbor Branch Foundation, Inc.; Institute of Marine Science, University of Alaska; Brookhaven National Laboratory, Oceanographic Sciences Division; Texas A&M University, Departments of Oceanography and Marine Biology; Florida Institute of Technology, Department of Oceanography and Ocean Engineering; and College of William and Mary, Virginia Institute of Marine Science.

The principal objective of the Second Joint American-Soviet Expedition was to determine the nonnatural changes in the structure and functioning of the Bering Sea Ecosystem and to assess its assimilative capacity. The main scientific goals were:

(1) biological, chemical, and physical base-line data were collected to provide a comprehensive profile of the Bering Sea;

(2) studies of the physiological and ecological characteristics of plankton organisms were conducted; and

(3) the relative ecological health of the Bering Sea was assessed.

In accordance with protocols of the Joint American and Soviet Meeting (Moscow - Tallin, 1984), the research vessel *Akademik Korolev*, with the Russian participants on board, arrived in Dutch Harbor, U.S.A., on 27 June 1984. During a two day port call, the American specialists and their scientific equipment were taken on board. The Second American-Soviet Expedition started on 30 June with transit to the southern polygon. Complex ecological studies were carried out in 20 stations of the 4

polygons. The route of the expedition and position of stations are given in frontispiece. The joint work and debarkation was completed on 31 July 1984 in Dutch Harbor. The entire duration of the Second American-Soviet Expedition to the Bering Sea was 36 days.

In accordance with specialties of the expedition's participants, six working groups were organized. At these meetings work schedules, joint studies and model experiments were planned. During the expedition, three meetings of the Scientific Council Board were held. Examined were: (1) ecological problems of monitoring studies of highly productive regions of the World Ocean; (2) the contemporary state of the knowledge of the Bering Sea ecosystem; (3) and preliminary scientific results of the Second American-Soviet expedition to the Bering Sea. In the course of the meetings, scientific reports of the American and Soviet specialists were presented.

During the Second American-Soviet Expedition to the Bering Sea, the following preliminary results were obtained:

The expedition's investigations were conducted during the period of late spring/early summer. Three to four distinctive water masses were identified for each polygon: surface, shoal, intermediate, and benthic.

For the deeper regions (Polygon I-South, Polygon IV - West) average surface temperatures were 7°-9°C. The thermocline was present at 25-30 m levels. The bottom layers were always about 1°C.

In contrast, the surface water temperatures for the northeastern part of the sea (Polygon II-East, Polygon III-North) decreased from south to north (7° to 2°C). In bottom water layers (50-85 m) a cold water pool (-2°C) was found. Here the thermoclines were shallower (10-15 m) and for the northern polygon, two overlapping thermoclines were noted.

The hydrochemical profile for Polygon I-South was characteristic for open ocean ecosystems. The high nutrient concentrations measured in surface waters increased with depth. Also, a layer of minimum oxygen always existed under the thermocline with another oxygen minimum at depths 200-500 m.

Along the transect between Polygon II-East and Polygon III-North, the nutrient concentrations of the surface waters decreased due to active phytoplankton production. In contrast, the bottom layers (45-60 m) had higher concentrations of ammonia which indicates active microbial degradation of organic matter. This trend was supported by microbiological studies.

In the deeper polygons, maxima of chlorophyll *a*, characteristic of phytoplanktonic biomass, were found at the 25-45 m levels. On the continental shelf, chlorophyll *a* maximums were recorded at similar depths, but at higher concentrations (10-25x).

The vertical profile of heterotrophic microorganisms was reflected in the distribution of the water masses. The greatest heterotrophic activity was associated with the surface layers down to a depth of 200-500 m.

Polygon III-North had the highest level of microbial degradation of organic matter in the photosynthetic zone (25-45 m). While in Polygon I-South, the rate of organic degradation in the photosynthetic zone was lower.

The microzonal character of the vertical distribution of zooneuston numbers was established. Maximum zooneuston concentrations were found in the thin subsurface layer (0.5 m), while lower concentration levels were found at the 5-25 cm level. Horizontal distribution of zooneuston was also uneven. The highest mean number of organisms was found in Polygon I-South. Polygon III-North had the lowest.

Microzooplankton concentrations were typically highest at the upper photosynthetic level. Peaks of vertical profile of infusoria distribution corresponded often to maximum phytoplankton levels. The mosaic structure of microzooplankton distribution was also noted. At Polygon IV-West, the upper 25 m were especially rich in infusoria, where their numbers exceeded 7.5 x 10^6 cells/m^3. Vertical distribution of seston was typical for summer period at the high latitude regions of the World Ocean. Seston maximum was found at 25-50 m and 100-200 m levels.

Rates of sedimentation of organic matter was estimated by the Uranium-Thorium equilibrium method and were different at each polygon. The highest rate of organic sedimentation was at the upper photosynthetic zones of Polygon III-North (795 mg C m^{-2} day^{-1}). The lowest sedimentation rates of particulates were noted at Polygon IV-South (447 mg C m^{-2} day^{-1}).

The estimation of complex-forming capacities of Cd and Cu in different water masses was also included in the program work. Estimation of labeled and non-labeled concentrations of these metals showed that the concentration of dissolved Cd changed from trace concentration (8 ng/L) to up to 67 ng/L. Vertical profiles of Cd distribution were characterized by high concentrations of this metal and the layers 10-100 m was 2-6x more concentrated than in the upper levels. The Cu-complexation decreased with the depths from 2.2 ng Cu^{2+}/L down to trace levels. The highest concentration of Cu-complexation was detected in the shallow regions especially in the vicinity of Polygon III and in the areas of the most phytoplankton biomass.

The study of benthic samples taken during the cruise characterizes the Bering Sea as a region of rich benthic fauna. While spatial distribution was uneven, representatives of 11 taxons and 21 classes of invertebrates were enumerated. Polychaetes, crustaceans, amphipods, ophiuras, and bivalves were the most abundant.

During the expedition 8 species of marine mammals and 29 species of marine birds were noted. All species recorded except for the Swinhoe's storm petrel were typical inhabitants of this region. The densities of the birds were especially high in the northern region adjacent to St. Lawrence Islands (about 12 birds per km^2). In the other regions, the indices of bird densities were lower (2-6 birds per km^2). St. Lawrence bird populations had an increased supply of prey on which to feed upon.

Short-term model experiments measured the higher adaptive capacities of microzooplankton in the surface water for the purposes of ecological screening of water masses and of determining the effects of critical levels of heavy metal impact on plankton communities of the Bering Sea under natural condition. Joint American-Soviet experiments utilizing interdisciplinary approaches evaluated simultaneous effects of nutrients and toxicants on planktonic communities under natural conditions. A decrease of the toxic effect of copper on microzooplankton was found in the presence of high concentrations of nitrate. Further, joint experiments were conducted and it was shown that during this experiment the combined effect of higher concentrations of nitrate and phosphate on the changes of several structural and functional characteristics of Bering Sea plankton was investigated. The data generated will be used to elucidate the role of nutrients and succession processes taking place on the frontal zone borders and during upwellings.

Some experiments assessed the effect of various organic toxicants on the rates of heterotrophic assimilation of organic matter. In some polygons, the stimulating effect of benzo(a)pyrene on the rates of heterotrophic assimilation of CO_2 by microorganisms was found.

The investigations that have been carried out during the Soviet-American expedition allow a preliminary characterization of the ecological situation in the Bering Sea as good, and the Bering Sea itself can be related to the pristine regions of the world ocean. High productivity, a great variety of many processes and comparably low ecological stability to external impacts are typical for this high latitude Arctic-Boreal basin. The following facts prove this suggestion:

1. A great abundance of microzooplankton that is typical for highly prodictive regions of the world ocean (e.g., upwellings, frontal zones);

2. A high rate of biosedimentation of organic matter from the "active" layer of the sea which is comparable with data characteristic of the most productive area of the world ocean;

3. A high sensitivity of different planktonic groups to toxic heavy metals, chlorinated organic, and polyaromatic hydrocarbons, which exemplifies natural conditions of the marine environment;

4. The most probable number of heterotrophic saprophytic micro-organisms in the Bering Sea is low in comparison with other regions of the world ocean. This amount consists of 10 cells/mL or less; indicator organisms (benzo(a)pyrene-oxidizing, paraffin-oxidizing, and PCB-oxidizing bacteria) have patchy distributions in very low concentrations which exemplifies autochthonous origins of these microorganisms in the areas studied; data on heterotrophic assimilation of CO_2 by microorganisms established that the activity of microorganisms is low (1-10 $\mu g\ L^{-1}\ day^{-1}$) in the areas investigated. These low rates are considered typical for Arctic and sub-Arctic zones of the World Ocean; the potential capability of microorganisms to oxidize different toxic organic materials was found to be temperature dependent; therefore, due to the low temperature regime of the Bering Sea, anthropogenic pollution of this region of the World Ocean could lead to dramatic ecological consequences.

At the end of the joint expedition on board the *Akademik Korolev*, there was an exchange of preliminary data. The future exchange of the joint analysis of data between American and Soviet scientists will occur in a series of 3 exchanges: (1) 1 January 1985, (2) 1 March 1985, (3) 1 July 1985.

The two sides had agreed that the data obtained and the results of analysis belong to both sides. Any publications based on these materials should indicate that the results were generated during the Second Joint American-Soviet Expedition to the Bering Sea. Both sides considered it useful to prepare and publish the joint compendium containing the final analysis of the American-Soviet research of the 1984 Expedition to the Bering Sea.

The American side has invited six Soviet specialists for about 2 weeks to the United States during the second half of 1985 to discuss the results of the cruise and to begin discussion for the preparation of book. The participants of the expedition felt that another meeting should be held in 1986 in USSR devoted to further discussion of the preparation for the final manuscript of the book *Investigation of the Bering Sea Ecosystem: Part II.*

Soviet and American participants expressed their interest in further development of joint research and consider it worthwhile to carry out further joint expeditions aimed to the fundamental studies of the ecological situation in the Bering Sea and other highly productive

regions of the Pacific Ocean. With this aim, the participants of the Second American-Soviet Expedition to the Bering Sea recommended to begin planning for the Third American-Soviet Expedition in the Pacific Ocean including the Bering Sea and highly productive ecosystem of the coral reefs.

Both sides note with satisfaction the friendly and constructive atmosphere of the expedition's work and the effectiveness of joint observations allowing for a wide complex of oceanographic and ecological studies.

The American delegation would like to express their sincerest thanks and gratitude to the Captain and crew of the *Akademik Korolev* for their hospitality and cooperativeness. In particular, the American delegation thanks the Captain for respecting the religious, dietary traditions of our members.

The American delegation thanks the Soviet delegation for providing an atmosphere of mutual respect, productive collaboration, and fruitful exchange of data. The associations established on this cruise will result in the exchange of data and information for many years to come.

The Soviet participants of the expedition express their sincere gratitude and thanks to the American specialists for fruitful and productive cooperation during the joint investigations of the Bering Sea.

This protocol was written in English and Russian and was signed on board the research vessel *Akademik Korolev*, 30 July 1984. Both texts are equally authentic.

For Soviet Side:

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The Leader of Project for the USSR Side.
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The Leader of Project for the American side.
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H.J. O'Conner

(This text is a reproduction of the protocol written on board the RV *Akademik Korolev* in 1984. The original was signed by both project leaders.)

APPENDIX A

Participants of the Second Soviet-American Expedition in the Bering Sea aboard the RV Akademik Korolev

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APPENDIX B

Temporary Electric Power Supply on Board the RV *Akademik Korolev*

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Introduction

Because the ship power supply on board the RV Akademik Korolev was designed for a 380-220-volt 3-phase 50-Hz ac output and the equipment of the U.S. scientific team (computers, oceanographic instrumentation, etc.) required 115-volt single-phase 60 Hz ac power, it was necessary to provide a suitable alternative electric power supply.

Based on an unfavorable experience during the 1977 RV Volna expedition, when electromagnetic interference (EMI) caused some loss of data, current expedition organizers recognized that a certain degree of EMI protection had to be provided. Also, operational deviations from the standard values of voltage and frequency, which can have a detrimental influence on computer performance, needed to be minimized.

System Design

The system schematics (Figs. 1 and 2) depict the following components:

1. Normal power supply by a motor-generator set (MG set) powered by the ship's electrical system

2. Stand-by supply from diesel generator

3. Emergency supply (50 Hz) from ship's electrical system through two isolation transformers

4. Two power conditioners

5. Necessary switch gear, cabling, receptacles, etc.

Power Disturbances

The following types of power disturbances must be considered in an electrical system:

Power interruptions
Voltage variations, including transients
Frequency variations
Voltage spikes
Electromagnetic interference (EMI).

Other disturbances, such as electromagnetic pulses, harmonics, etc., can be discounted for this application. A distinction that must be made is the one between induced and conducted interference, particularly in connection with EMI.

Power interruptions are, of course, the most difficult disturbances to deal with. A full protection against a complete loss of power is only available from an uninterrupted power supply (UPS). These are battery-backed power-supply systems that are constantly activated; the main power serves in principle only to keep the batteries charged. Thus, even if the main power is interrupted, the batteries supply the computers with electric power via an inverter for a certain time, and duration depends only on the capacity of the batteries. A UPS system, although ideal even with regard to

other disturbances, is extremely expensive and heavy and requires also a certain amount of attention. It was, therefore, excluded from the recommendations as a temporary power supply.

Brief time interruptions in the order of milliseconds can be effectively bridged by a motor-generator set (MG set). A motor powered by the ship's electrical system drives a generator that supplies the required power to the computer equipment. The inertia of the rotating masses of the motor and generator supply the energy necessary to bridge a short interruption of the ship's system. A minimal drop in frequency must be expected because rotational speed decreases slightly. However, electronic equipment has, in general, a larger tolerance for frequency variations than for voltage variations.

The MG set provides complete galvanic separation between the ship's system and the computer equipment. Thus, any type of conducted interference from the ship's system to the computers is prevented.

In addition, it is possible to overcome the differences of voltage and frequency between the available and the required electrical system by using a V-belt drive between motor and generator. A correctly selected transmission ratio (in this case 1.631:1) permits the generator to turn at 1,800 rpm while the motor operates at 1.631 x 1800 = 2,936 rpm. This is the asynchronous speed of the motor at approximately half-load of the MG set, with the motor connected to the 50-Hz ship system.

Voltage variations, both long and short, were minimized by using a generator with compound excitation and superimposed voltage regulation. This type of generator provides a constant or even slightly rising voltage with increasing load, which compensates for voltage drop in cables downstream of the generator. The reaction time is very short, because the cause for a disturbing voltage dip, namely the current, is used to boost the excitation, an effect which is called "compounding," at the same moment when the current occurs. This boost of excitation is a fast but not an accurate way to provide the necessary excitation energy. For that reason an additional superimposed voltage regulation must be provided. This type of voltage regulation (with rising voltage at rising load) does not lend itself readily to parallel operation with other generators. In this case, parallel operation was not required.

The power supplied by the generator, even with the voltage regulation described above, was not considered "clean" enough, particularly because two laboratory complexes spatially removed from each other had to be supported. It was decided to provide one power conditioner for each laboratory complex (forward and aft) in order to improve the quality of power for each area. These power conditioners are isolation transformers with double shielding between primary and secondary windings. On the primary side, they contain a solid-state voltage regulator, which is extremely fast acting (sensing time in approximately 2 ms, corresponding to less than one-fourth of a semi 60-Hz half-wave response time after sensing generally less than one half-cycle).

Voltage variations caused by starting currents of a motor (one winch motor had to be supplied from the aft power supply) were minimized by providing an extra feeder cable to the winch motor. The effect of the starting current of the motor was thus dampened by the impedance of the feeder cable.

The primary feeder voltage into the power conditioners was 220 V, 60 Hz; the secondary distribution voltage was 115 V, 60 Hz, all single phase.

Frequency variations were minimized by using an oversized induction motor for the generator so that the asynchronous speed drop of the motor, which is directly responsible for the frequency drop at varying loads, was kept small. Any frequency variations in the power system of the ship were fully transmitted to the computer system. This could not have been

avoided except by use of a UPS. In practical application during the expedition, however, no ill effect was experienced, and observation of the frequency did not reveal any adverse deviations.

The speed drop of the standby diesel generator was adjusted to a minimum at the factory.

Voltage spikes, which are very high voltage peaks, possibly above 1,000 V of microseconds duration, can be extremely damaging and can cause both data loss and equipment damage. They were suppressed at the primary and secondary sides of the isolation transformers in the power conditioners. Electric power equipment is tested with relatively high test voltages and is therefore better equipped to deal with such spikes than electronic equipment with its low-level signals and sensitive solid-state components.

Electromagnetic interference and other electrical "noise" can be of either low or high frequency. It can be induced from the outside when cables and equipment act as receiving antennae, or it can be conducted when cables act as transmission lines for electrical noise already in the system. Furthermore, one distinguishes between "common-mode" and "transverse-mode" noise, common mode being noise against ground potential and transverse mode being measured between conductors. The power conditioners were provided with an electrical filter system for both common-mode and transverse-mode noise. These filter systems, however, required that one conductor of the 115-V system had to be grounded, which is unlike normal electrical systems on ships. Since the difficulties during the Volna expedition were caused by common-mode noise, we decided to use the common mode noise suppression of the power conditioners and to ground one conductor of the system secondary of the conditioners. It was also mandatory to have only one ground point in order to reap the full benefit of the power conditioners. In connection with that policy, it was decided to have only one ground conductor that would take over the function of safety ground and shield. The cable selected for the distribution secondary of the power conditioners was a two-conductor cable with shield, in which the cross section of the shielding braid was at least as large as the cross section of each conductor, so that full protection against shock was assured. This measure, although unorthodox, prevented any formation of ground loops. It did require careful installation and instruction of the scientists in the use of the system. The combined effect of the above measures more or less guaranteed EMI protection up to approximate 1 MHz of noise, considering the cable lengths involved.

Higher frequency noise would have required multiple ground points in order to decrease the high-frequency impedence of the ground connection. However, that would have negated the effect of the power conditioners. Since such frequencies are mainly induced from high-frequency communication (short-wave radio) and since most of the cables were installed below deck, and so not exposed to such radio frequencies, the need for multiple ground points was not apparent. Experience later during the expedition showed that one computer was sensitive to high-frequency noise during the vessel's communication with the home port with a very powerful short-wave transmitter. Complete shielding of the entire computer by a grounded Faraday cage might have improved conditions.

The manufacturer of the power conditioners extended the warranty for the conditioners even if disconnection of one line from the ground inside the conditioners was disconnected, in order to retain an ungrounded system.

System Description and Function

The normal power supply (Fig. 1) from the ship's system is 3-phase, 380-V 50-Hz alternating current. A circuit breaker connects the drive motor of the MG set with the ship's electrical system. Once the motor is energized, the generator supplies single-phase, 220 V, 60 Hz power through a contactor to the interlock switch. The contactor coil is energized by the 380-V, 50-Hz power. Thus, upon failure of the

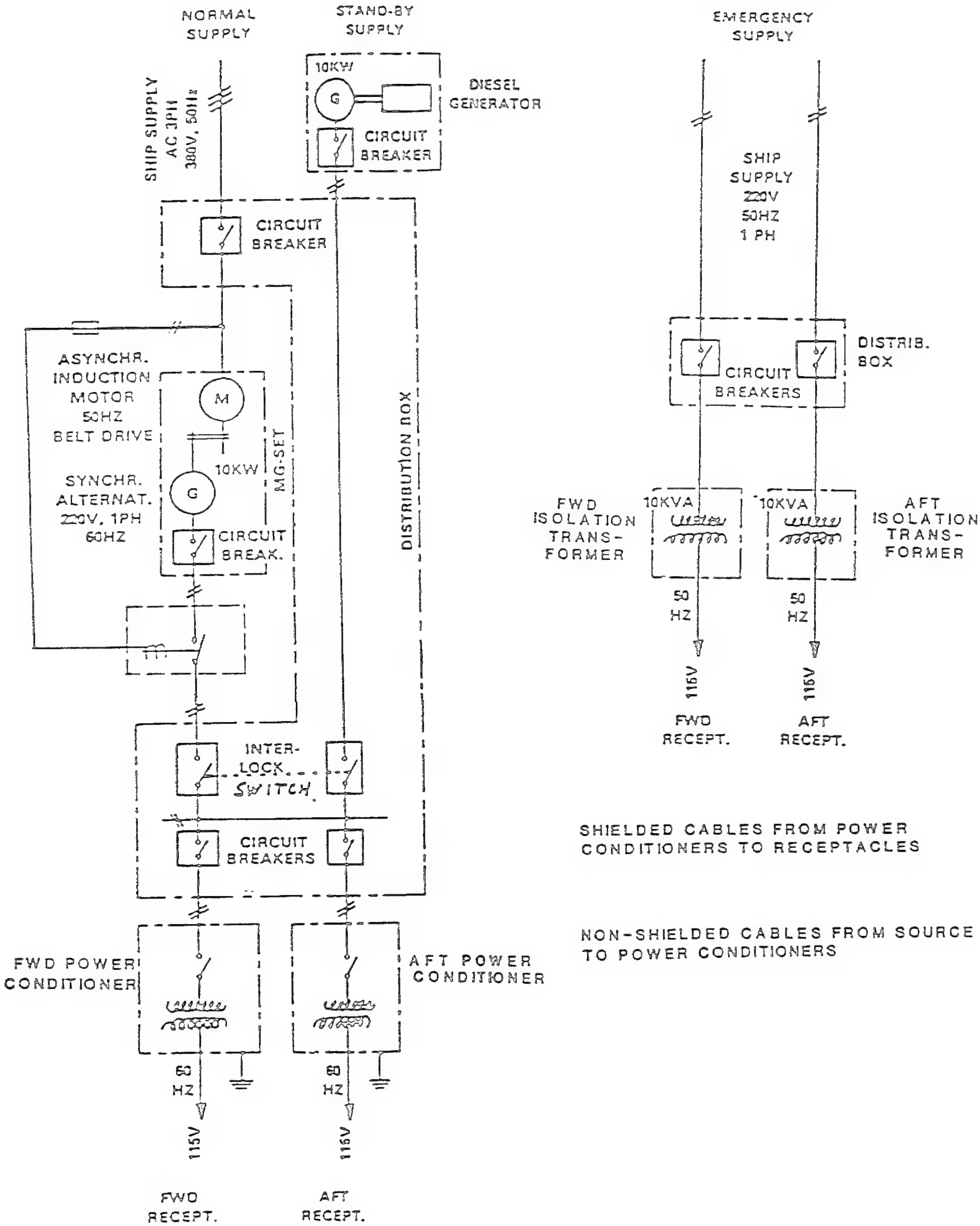

Fig. 1. Schematic diagram of electric power and distribution system.

ship's supply, the contactor drops out and instantly disconnects the equipment from the generator. This prevents any user overload when the frequency decreases with decreasing speed of the deenergized motor of the MG set,while the generator voltage is still kept up for a certain time by the automatic voltage regulator. The interlock switch serves to prevent simultaneous operation of the MG set and diesel generator, also shown in Fig. 1 as the standby supply. Two circuit breakers downstream of the interlock switch feed power to the forward and aft power conditioners. Energized by the 50-Hz ship's system, it produces 115 V, 50 Hz for that equipment which is not sensitive to 50-Hz operation.

Figure 2 shows both power conditioners, forward and aft. All cables upstream of the power conditioners are of the nonshielded variety, while all cables downstream of the power conditioners are of the shield type. The connecting cable from the distribution box to the aft power conditioner was rather long and was laid on the side deck of the ship outside of the superstructure. Therefore, it may have been exposed to HF-communication radiation, leading to the effect on one computer as previously mentioned. If this cable cannot be accommodated inside the superstructure of the ship at the repetition of such an expedition, it may be advisable to cover it with a separate shield.

System Assembly and Use

After the contract was issued, the equipment was purchased, with excellent support from all suppliers.

Preassembly was done in Washington, D.C., using measurements taken on board in Singapore during a ship survey to determine cable lengths. Cables were precut and connectors installed during preassembly. The preassembled system was shipped by air to Dutch Harbor, Aleutian Islands, Alaska, and stored there in a dry warehouse at the pier until the vessel's arrival. Installation on board went flawlessly with excellent support from the crew.

System start-up was successful. The MG set was in service for approximately one month and provided uninterrupted service throughout the entire expedition, neither diesel generator nor emergency power supply ever being needed. The voltage variation monitored repeatedly by Dr. Whitledge (Institute of Marine Science, University of Texas, Austin) through his computer interface (1,000 readings over a few seconds), was very small (less than 1%) on all tests performed. The electric power on board was more stable than in the laboratory where he normally worked.

Disassembly and Storage

When the expedition was over, the equipment was disassembled, taken off the ship and packed for shipment to Anchorage, Alaska. In Anchorage the equipment was repacked with 3-year storage in mind. The equipment must be checked and the desiccant material has to be replaced in three years in order to assure that no storage damage will occur.

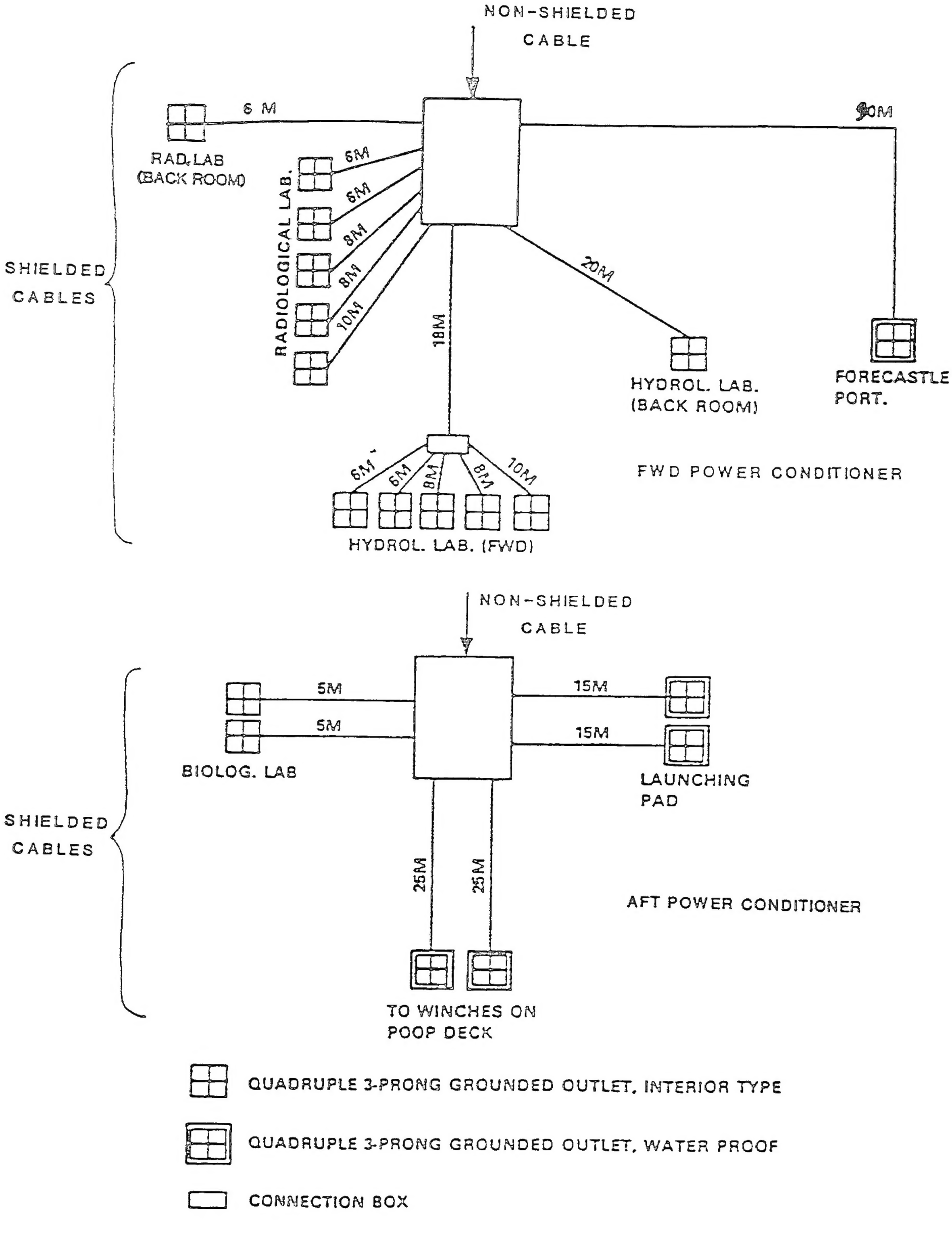

Fig. 2. Interconnection diagram of cabling on secondary side of power conditioners.

List of Companies Providing Services and Supplies

Diesel generator and MG set:
Engine Technology, Inc. (ENTEC)
704 Ginesi Drive
P.O. Box H
Morganville, N.J. 07751
Tel.: (201) 536-5100
(201) 566-4666
Contact: Hans Wietusch

Power conditioners:
Computer Power Systems Corp.
18150 S. Figueros St.
P.O. Box 6240
Carson, Calif. 90749-6240
Tel.: (213) 515-6566
Contacts: Milton Hanson, X 257
Wayne Wright

Representative for Computer Power Systems Corp.
NKA, Inc.
8905 Fairview Rd.
Silver Spring, Md. 20910
Tel.: (301) 585-1116
(301) 585-6141
Contact: Art Siegel

Electrician services, procurement of cables and other installation material and miscellaneous items.

American Systems Engineering Corporation (AMSEC)
2121 Crystal Drive
Crystal Park Two, Suite 607
Arlington, Va. 22209
Tel.: (703) 979-3322
Contact: W. Scott Hale

Roscigno, P.F., editor. 1990. **Results of the second joint U.S.-U.S.S.R. Bering Sea expedition, summer 1984.** U.S. Fish Wildl. Serv. *Biol. Rep.* 90(13). 317 pp.

Under the auspices of the 1972 bilateral agreement, U.S.A.-U.S.S.R. Agreement on Cooperation in the Field on the Protection of the Environment, project 02.05-41, "Biosphere Reserves—Bering Sea Ecosystem Studies," a joint U.S.-U.S.S.R. study of the Bering Sea ecosystem was conducted from 27 June to 31 July 1984. Oceanographic processes in the Bering Sea support a diversity of important natural resources. The main objective of the study was to characterize the physical, chemical, and biological profiles of the water, sediment, and biota of the Bering Sea. Researchers independently and collaboratively studied areas in both American and Soviet waters so that the very distinct water masses that characterize the entire region could be compared. By bringing together various scientific disciplines, project directors hoped that the relative ecological health of the Bering Sea could be assessed. This report summarizes the results of these investigations. The results are also presented in a Russian companion document.

Key words: Joint U.S.-U.S.S.R. expedition, international studies, ecosystem, chemical oceanography, birds, pollutants, Bering Sea, biological oceanography, physical oceanography, benthos, mammals, biotoxicology.

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